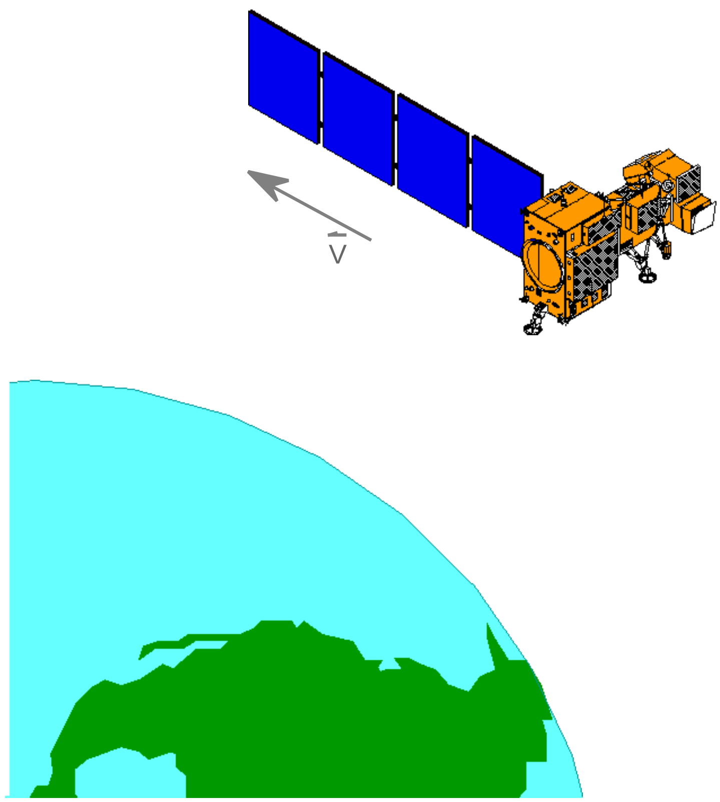
Landsat 7 Delta-i Report - 2000



Landsat 7 FOT

April, 2001

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I. Introduction/Summary

A burn was executed on 10/11/00 (day 285) to alter the inclination of the Landsat 7 orbit. To accomplish this, the spacecraft was slewed around its yaw axis 90.75° in order to orient the thrust vector (from its maneuver jets) perpendicular to the velocity vector. Inclination prior to the burn was approximately 98.175°. <u>The predicted change in inclination was to be 0.045 degrees.</u> A total of 42448 cumulative pulses on jets 1-4 were commanded (approximately 19 min 32 sec). Due to off-pulsing of these jets during the burn to control pitch and yaw, the pulses were distributed among the four jets 11184, 11722, 10040, and 9502 respectively. In addition, pulses were commanded on jets 6 and 8 (a total of 78 pulses each). Jets 5, 6, 7, and 8 were used to control the roll axis during the burn. After the burn was completed, the spacecraft was returned to a nominal yaw orientation (via a -90.75° slew). <u>The actual inclination change was 0.0467°.</u> Orbit inclination and Mean Local Node Crossing times from the beginning of normal operations to just after the Delta-i burn are shown in **Figure 1**. The ETM+ cooler door was moved to its "outgas" position to protect the radiative cooler from contaminates and as a mitigation against pointing the cooler at the sun in the event of a loss of attitude control. Closing the door to this position caused several specific elements in the ETM+ to heat past their operational ranges. A 27 hour ETM+ cooldown, with special calibration imaging, followed the slew-burn-slew sequence.

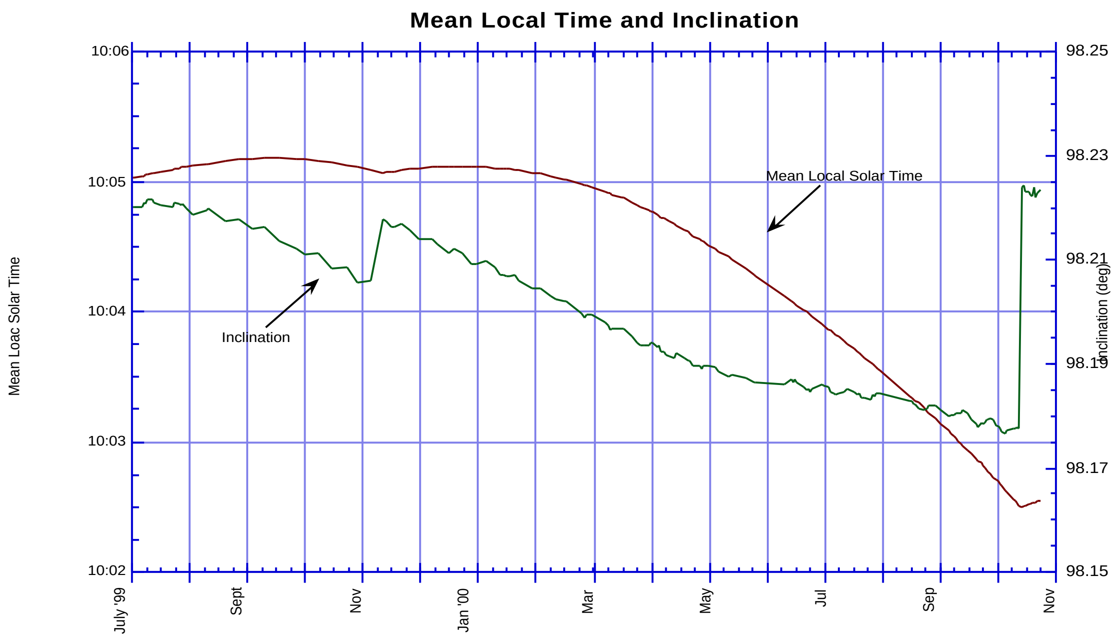


Figure 1 - Mean Local Time Crossing and Inclination

II. Preparation work

Several planning meetings were held and members from NASA, USGS, FOT, Flight Dynamics, LMMS sustaining engineering, and SBRS were involved. Operational plans, timelines (for product delivery and the maneuver itself), and decisions about prepping the spacecraft for the maneuver were all discussed.
Four new items were discussed prior to this delta-i.

1. The LPSO requested that ETM+ imaging be conducted during the cooldown period in an effort to calibrate data at various component temperatures. To accomplish this, a large effort was necessary in the Mission Planning area to ensure that only those images requested were taken (i.e. shut down the Long Term plan), and that these images were downlinked in contacts separate from "science" images still stored on the SSR.

2. The alignment of ACS components. In July 2000 a new alignment matrix was uplinked for the CSA. Alignment numbers for the CSA were measured prior to launch. In an effort to provide similar numbers for the gyros, a series of offset (±10°) slews were conducted in August, 2000. However, failing to reach a clear set of alignment numbers that could be agreed upon by all involved, the uplink of new values was postponed. The initial intent was to update the alignment matrices of the CSA and IMU prior to the delta-i maneuver in order to facilitate a quicker convergence of the precision attitude filter. However, it was decided by the group that the possible gain in uplinking new IMU alignment values was outweighed by the risk of using a set of numbers not agreed to by all parties.

3. The abort limit during maneuver mode was widened for the Pitch and Roll axes. During the 1999 Delta-i, the Roll axis reached an error of –2.6° with all systems performing nominally. It was felt that more margin was desired between "nominal" performance and the abort limit. A new limit of ±5.5° was agreed upon and uplinked prior to the 2000 Delta-i. Plans are to leave the limit at ±5.5° for all future burns.

4. The temporary IMU bias calculated by FSW is placed into housekeeping data as well as PCD. It is conceivable that this value, if large enough, could cause an overflow condition in the routine that places it into PCD. This overflow would halt the SCP. It was unknown how large the IMU tempbias might grow upon beginning the Precision control mode convergence after returning to our normal orientation. It was decided that the scale factor applied to the value would be altered prior to the delta-i sequence to ensure it did not grow too large for FSW to handle. The MOC was temporarily altered to convert the value using the scale factor. After Precision control had been re-established, the scale factor in FSW and the MOC were returned to normal.

In addition, simulations were conducted on LSIM in an effort to characterize what sort of behavior might be seen during the slew/burn/slew sequence. On-orbit experience with the PRADS filter combined with LSIM data and results from a star transit prediction tool were used to draft a clear timeline for regaining precsion attitude control.

Several of the configuration and set-up issues resolved prior to the 1999 Delta-i were followed again:

1. The Delta-i maneuver should take place while the ground track error is a few kilometers “West” of nominal center (i.e. we have a negative WRS error). The burn was certain to add a large eastward drift rate to the error, and in fact, a delta-V maneuver was planned for two days after the Delta-i to take care of the increased drift. The eastward drift is created intentionally using the yaw angle larger than 90° to avoid imparting a westward drift. A westward drift could send the s/c outside of its ±5km WRS requirement with no recourse but to wait for atmospheric drag to lower the orbit in order to reverse the drift. The only other way to reverse westward drift is to perform a retrograde delta-V which involves a 180° yaw slew.

2. Since jets 1-4 were to be used for the burn and we normally only exercise jets 1 and 3 in our delta-V burns, we switched to thruster configuration 7 for the last three delta-V burns prior to the Delta-i burn to gather data on the performance of jets 2 and 4.

3. In previous 4 jet burns, a negative yaw transient had been seen during the burn and was consistent in most burns. In addition, the burn angle was to be biased in order to ensure an *eastward* drift of WRS error after the Delta-i. Adding to these two factors the estimated jet misalignment, and it was decided to increase the nominal 90° yaw slew to 90.75°.

4. It was decided that the Delta-i was to be performed during a descending path. An ascending path was considered because it meant stopping the solar array during a shadow, minimizing power balance effects. This plan was rejected by the group due to solar array cooling concerns. With the array stopped in the 0° position (as it should be during all 4 jet burns), it remains edge on to the Earth, making it to cool faster and deeper than it would if the array were rotating. Using past data, it was determined that the array at the 0° position during an entire shadow period would cool it well into its yellow limit range. Over time Large temperature transients like this could alter the properties of the glue used to bond the solar cells to the substrate. To avoid abnormal temperature transients it was decided to execute the burn during a descending path, in daylight.

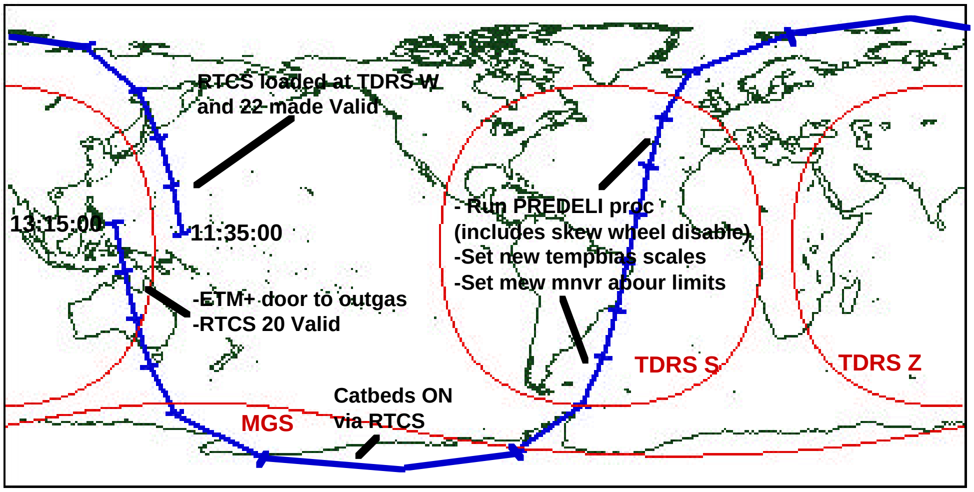
5. The ETM+ cooler door was closed one stop to the Outgas position. This was to protect the cooler door against contamination. A recommendation was made during the post-launch orbit raising maneuvers that burns not executed at a nominal yaw angle should be done with the ETM+ cooler door in the Outgas position. In addition to contamination issues, this ensures the immediate protection of the ETM+ radiative cooler against sun impingement in the event of loss of attitude control. The timeline executed for the 2000 Delta-i allowed the cooler door to remain in the Outgas position for a shorter amount of time than in 1999. This limited heating effects on the Cold Focal Plane (CFPA).

The final effort in preparing for the Delta-i was training. A Delta-i training package was generated for the FOT to give background information on Delta-i maneuvers and our implementation. In addition to this package, dry runs of the entire sequence were executed using the simulator (LSIM) for any personnel that would be present for the actual burn sequence.

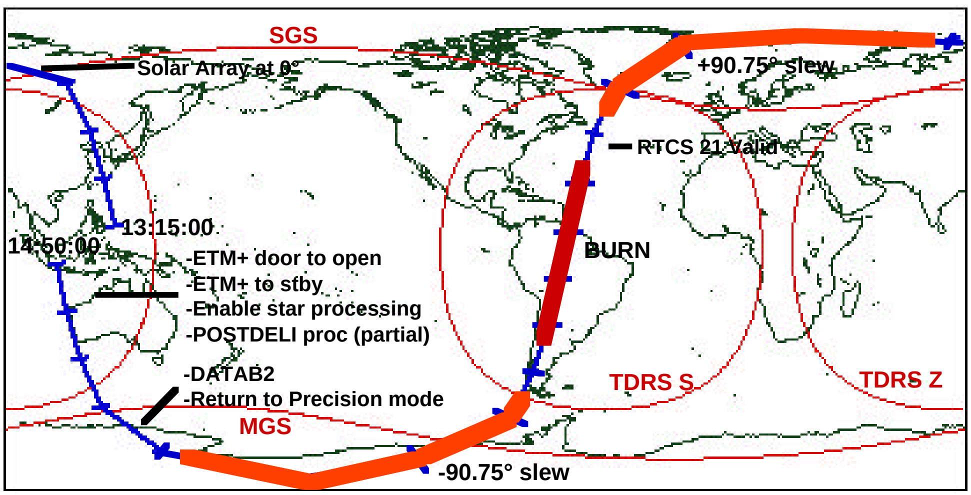
III. Sequence summary, map, and timeline

Below is a high level sequence of planned events over three orbits.

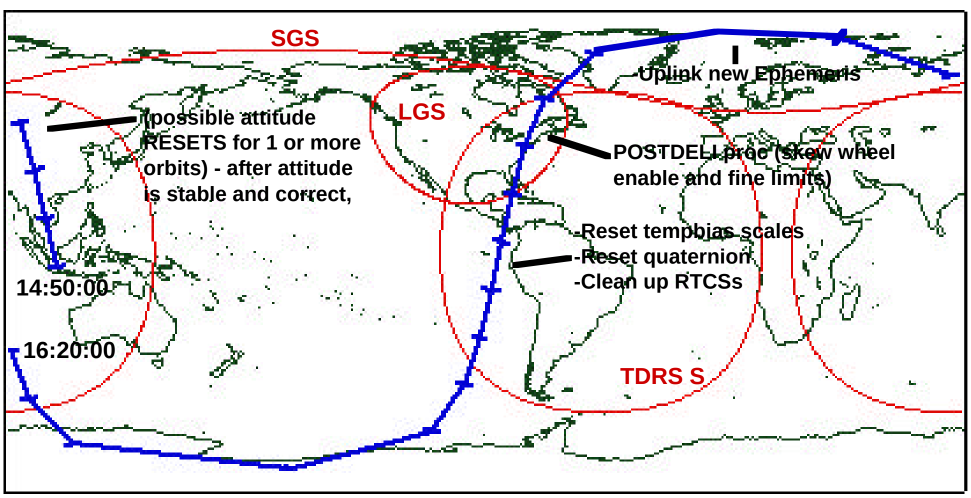
Orbit 7935



Orbit 7936



Orbit 7937



Delta-i #2 Report (October 2000)

Following is a timeline of events as executed. Appendix A contains a more detailed events listing. **All times in this report are GMT.**

Delta-i sequence summary (as performed)

285-12:12:04.9	Skew wheel = DISABLED
285-12:33:00.0	Skew wheel reaches 0 RPM
285-12:14:07.4	TEMPBIAS scale changed to x’0020’
285-12:16:32.6	Abort limits changed to +/- 5° on SCP 1
285-12:18:40.4	Abort limits changed to +/- 5° on SCP 2
285-12:52:42.2	Prime/Redundant Catbeds ON
285-13:05:54.5	ETM+ cooler door at OUTGAS
285-13:16:33.8	Solar Array to Open Loop, Slew Fwd
285-13:23:45.8	Solar Array to Cmd Position, 0 deg
285-13:30:22.0	Solar Array slows to FAST
285-13:31:23.0	Solar Array at Index position
285-13:35:04.3	entered DATAB_1 state
285-13:35:38.2	entered SLEW state
285-13:48:00.0	Yaw slew Ends
285-13:52:44.3	Burn Starts; RTCS 21 = ACTIVE
285-14:12:16.9	Burn Ends; ACS mode = Precision
285-14:17:40.0	Yaw slew starts
285-14:29:30.0	Yaw slew ends
285-14:30:04.6	Entered DATAB_2 state
285-14:30:50.3	entered PRECISION state
285-14:31:11.2	Enable Star processing
285-14:31:50.9	Solar array in Ephemeris mode
285-14:42:52.0	ETM+ cooler door in Open position
285-14:44:46.0	Full Reset of PRADS filter
285-14:48:26.6	ETM+ in STBY mode
285-14:49:08.0	CFPA htr DISABLED
285-14:49:26.3	Blackbody htr DISABLED
285-14:49:48.9	Baffle htr DISABLED
285-14:52:44.4	Prime/Redundant Catbed htrs OFF
285-15:14:14.5	Post-burn Ephemeris uplink complete
285-15:19:06.9	Skew wheel = ENABLED
285-15:20:13.3	ACS limits = FINE
285-15:25:17.5	PRADS filter converged
285-15:28:18.1	Reset TEMPBIAS scale values
285-15:43:29.6	entered DATAB 1
285-15:46:20.0	Reset Slew Quaternion
285-15:46:51.8	entered DATAB 2 state
286-01:24:02.5	Blackbody htr ENABLED
286-01:24:37.9	Blackbody T3 selected
286-09:42:19.7	Baffle htr ENABLED
286-17:47:29.1	CFPA htr ENABLED

IV. Spacecraft performance

Overall, the spacecraft performed as expected during the entire sequence. Below is a breakdown of different areas of spacecraft performance.

ACS Performance

Skew Wheel Spindown/Spinup

During long thruster firings, as a precaution to abnormal jet firing, an additional safety margin in system momentum unloading capacity is sought which will keep the total spacecraft momentum from building up beyond the saturation limits of the Reaction Wheel Assembly (RWA). This additional safety margin is achieved by “spinning down” the skew wheel prior to the Delta-i’s long thruster firing sequence. The spin down consists of disabling the spacecraft’s skew reaction wheel bias within Flight Software (FSW) which has the affect of driving all the wheels toward 0 RPM.

While the FSW was operating in the PRECISION ACS submode, the skew wheel was spun down toward 0 RPM starting from its nominally biased value of 1922 RPM. The operation started at 2000/285-12:12:04 and ended at 2000/285-12:32:28. The total spin down time was 20 minutes 24 seconds, which was slightly outside the 20 minute TDS contact that had been scheduled. Upon removal of the skew speed bias ALL wheels headed toward 0 RPM. In 1999 the skew spin down started from a lower RPM setting (1272 RPM) and completed in approximately 13 minutes. However, the rate of spin down in 1999 and 2000 were unchanged, at approximately 100 RPM/minute. **Figure 2** shows a nominal speed profile of ALL 4 wheels during and several minutes after the skew spin down.

Note: In general, the ACS section uses the subscripts (0), (1), and (2) to represent the Roll, Pitch and Yaw axis, respectively, in the spacecraft navigation frame; the subscript (4) is used for the skew “axis”.

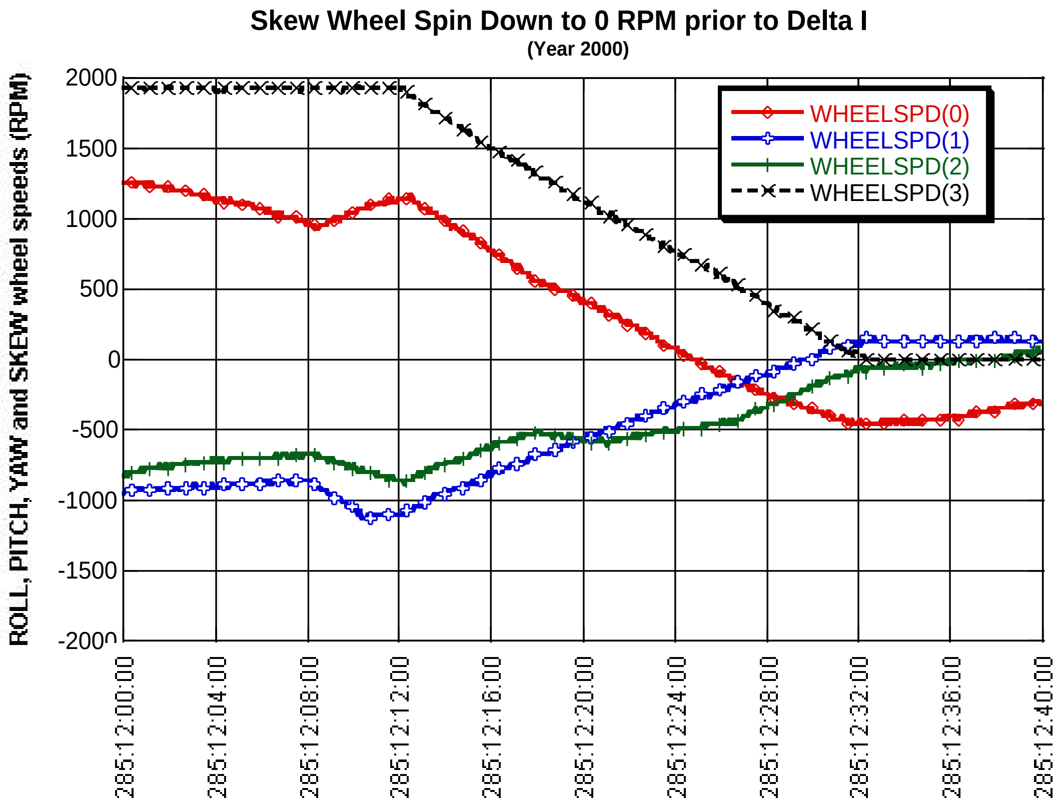


Figure 2 – Skew Wheel Spin down to 0 RPM prior to "Slew-Burn-Slew"

Upon completion of the Delta-i sequence, the Skew wheel bias was reapplied. Starting from 0 RPM, the skew wheel achieved its nominal bias 2 minutes 10 seconds after command execution and a steady state had been reached within 10 minutes 38 seconds. At this time, all wheel speeds were safely driven away from 0 RPM and as had been the case prior to the Delta-i, nominal friction levels were reestablished. **Figure 3** shows wheel speeds during skew wheel spin up during 1999 and 2000.

Comparison of Wheel Recovery at the completion of the 1999 and 2000 Delta I sequences

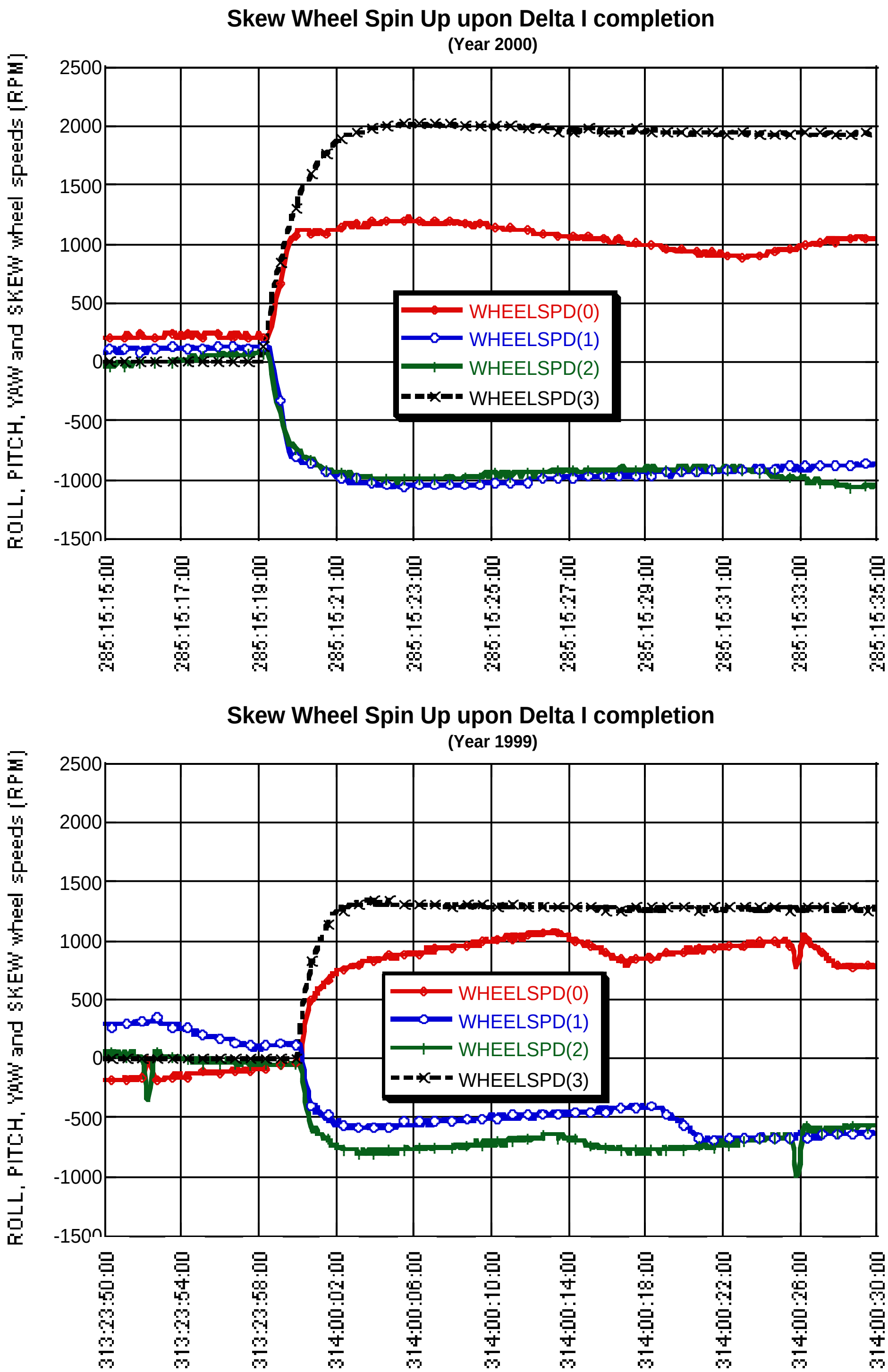


Figure 3 – Skew Wheel Spin up after "Slew-Burn-Slew"

During the spin down, the spacecraft attitude and rate signals remained in a nearly unperturbed state. **Figures 4** and **5** depict very steady state attitude and rate errors within the PRECISION control law, with the exception of the transients observed at spin down start and stop. As expected, the Yaw axis had the most stable attitude response during spin down, as it is the axis with the greatest inertia. Meanwhile, Pitch and Roll attitude response signatures were slightly more pronounced at the spin down start and stop points. Roll having the least inertia and Pitch carrying orbit rate were most perturbed during these times; of these, pitch yielded the greatest error though it never exceeded ±0.013 degrees. On all axes, attitude perturbations were settled within 2 minutes of the response start. Rate error response was less eventful and **Figure 5** shows tight control during spin down. Though Roll rate seems to be the least behaved of all, its control is still approximately within ±0.003 degrees per second and well within specification. The other two axes demonstrate less rate error but their signatures seem "noisier". This is explained by Flight Software (FSW) clamping very small numbers to 0 in telemetry, in order to avoid a computer underflow condition during on board telemetry compression.

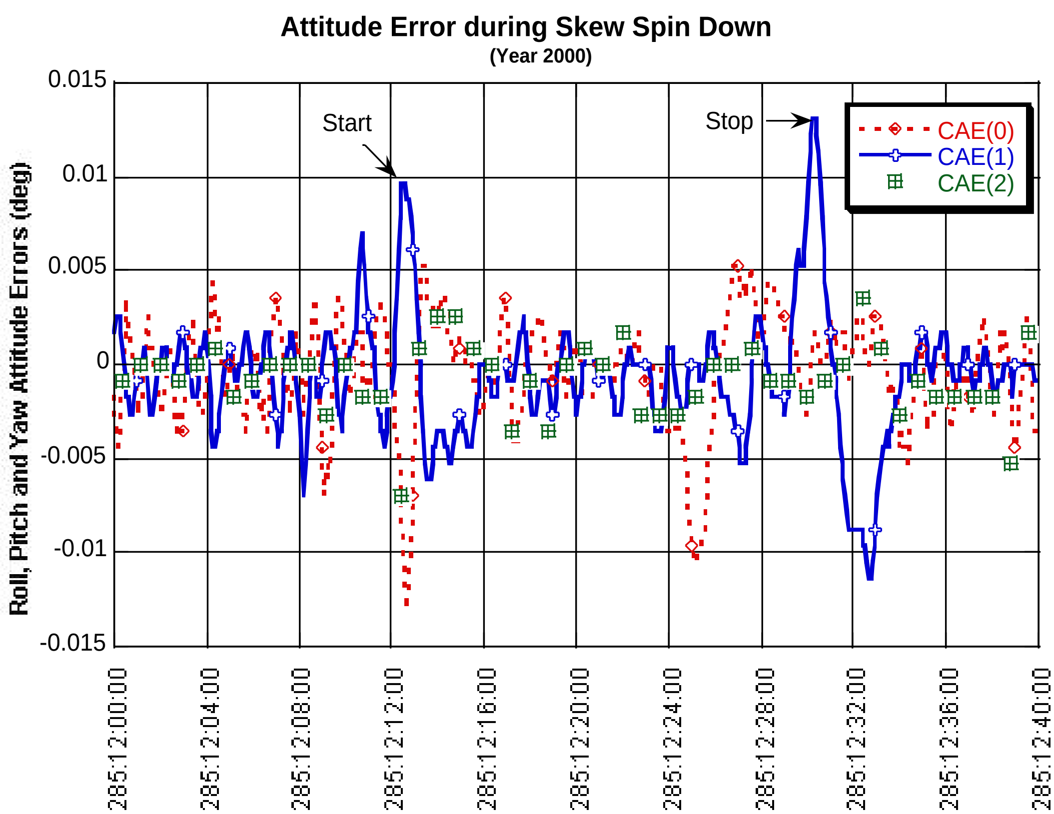


Figure 4 – Attitude Error during Skew Spin down

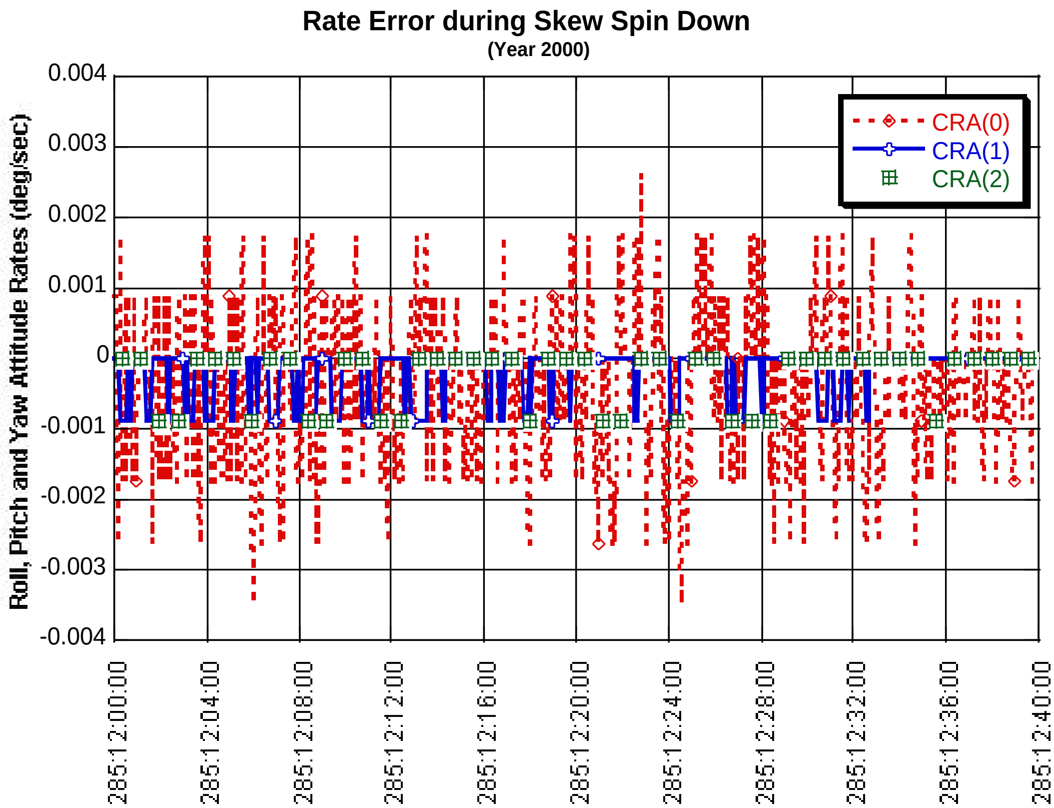


Figure 5 – Rate Error during Skew Spin down

The operation of spinning the skew wheel down is accomplished by disabling the torque commands sent by the FSW to the skew wheel. **Figure 6** shows the effect of commanding zero torque on the skew wheel. Upon skew spin down, the effect on the remaining wheels amounts to very fine adjustments to the wheel torque commands for Roll, Pitch and Yaw. As the saturated torque command is equivalent to ±256 counts, in all instances the wheels were very gently commanded to their new settings at a fraction (±20 counts) of the maximum torque capacity. After the spin down completes, the Roll torque is inverted and the Pitch and Yaw torques are hovering about null. This profile is also highlighted by the wheel speeds in **Figure 2** and further supported by **Figure 7**, which represents the current wheel friction as computed by FSW. **Figures 8** and **9** show wheel friction during skew wheel spin up.

Wheel Torque Commands during Skew Spin Down
(Year 2000)

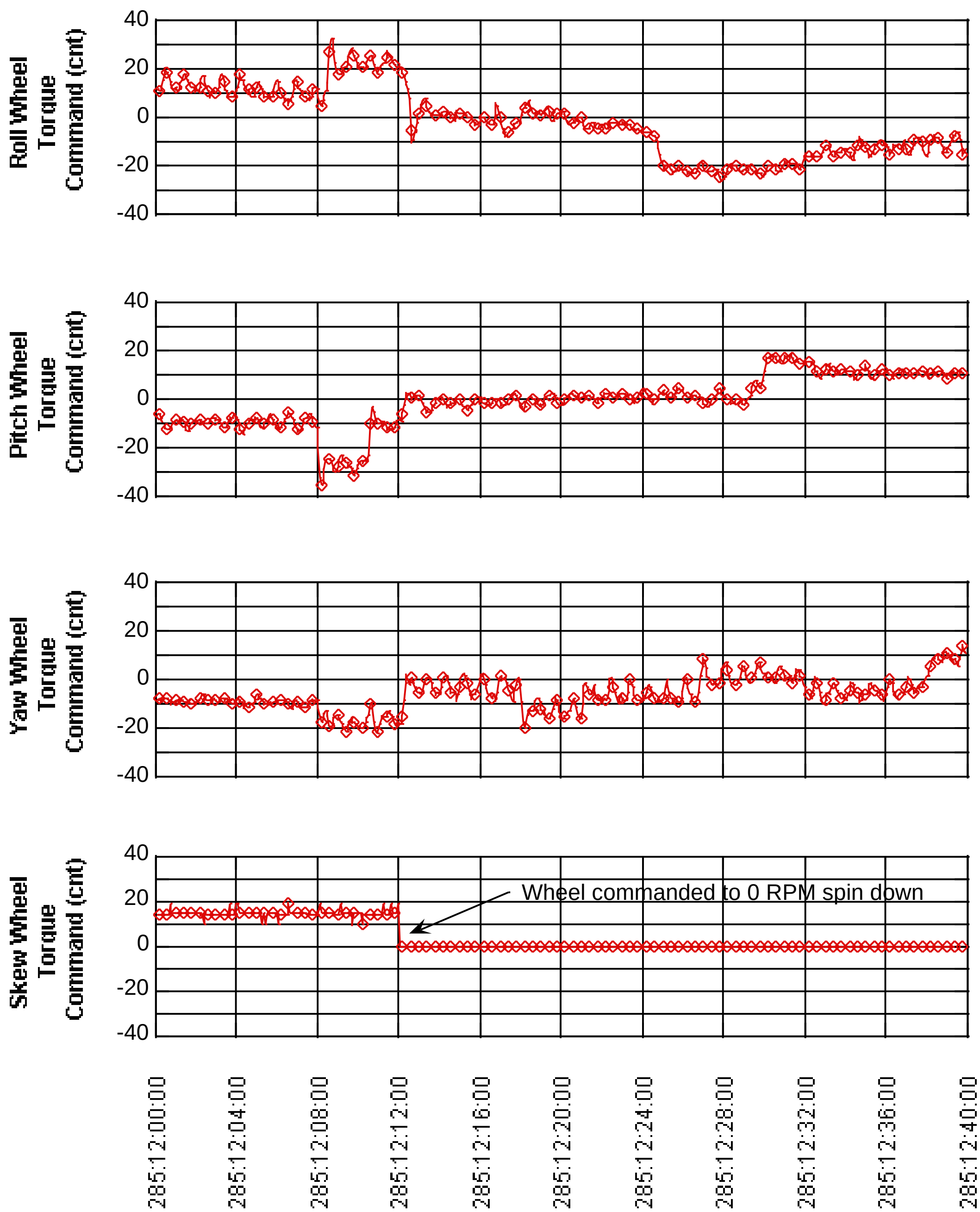


Figure 6 – Wheel Torque Commands during Skew Spin down

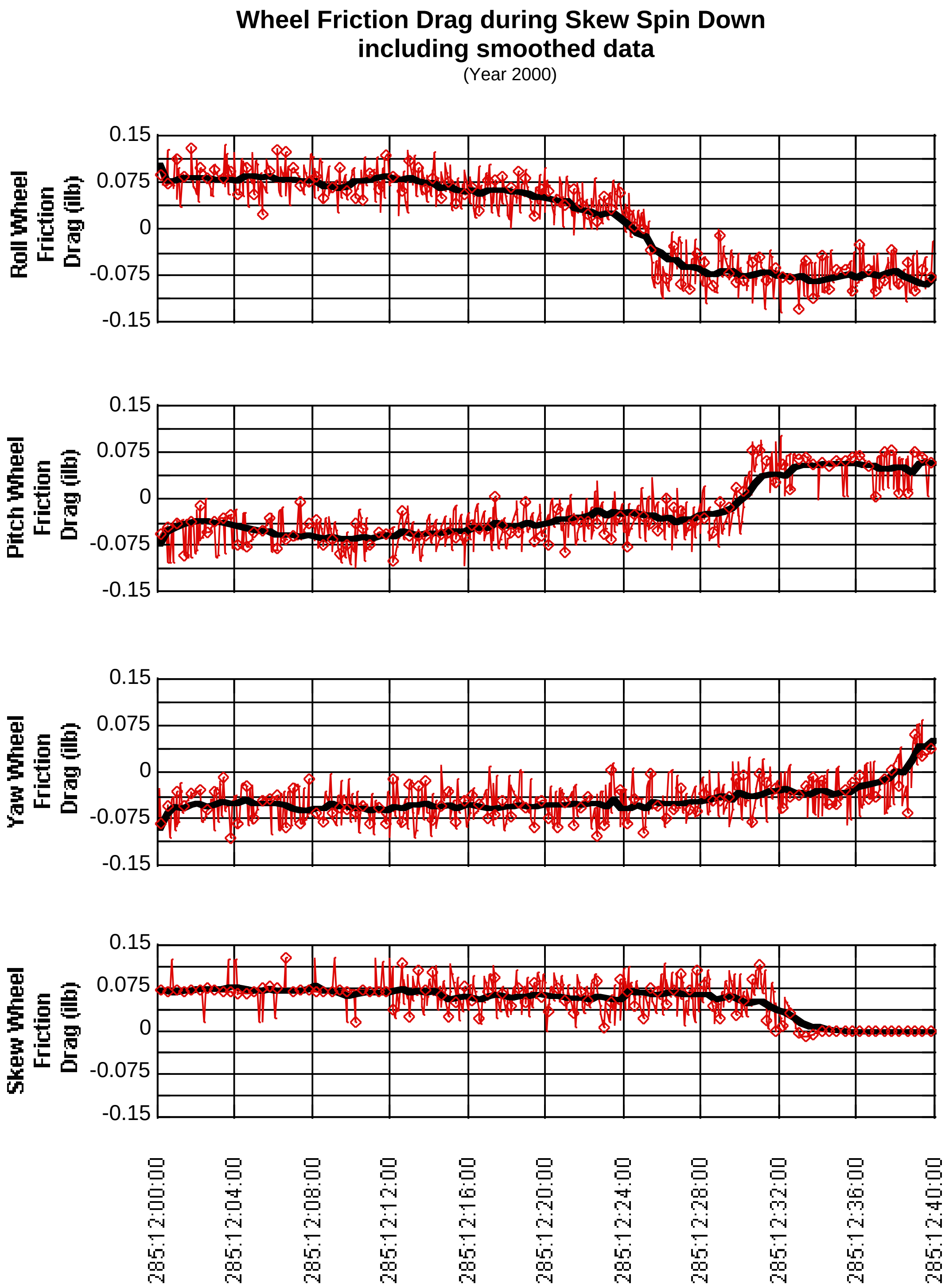


Figure 7 – Wheel Drag during Skew Spin down

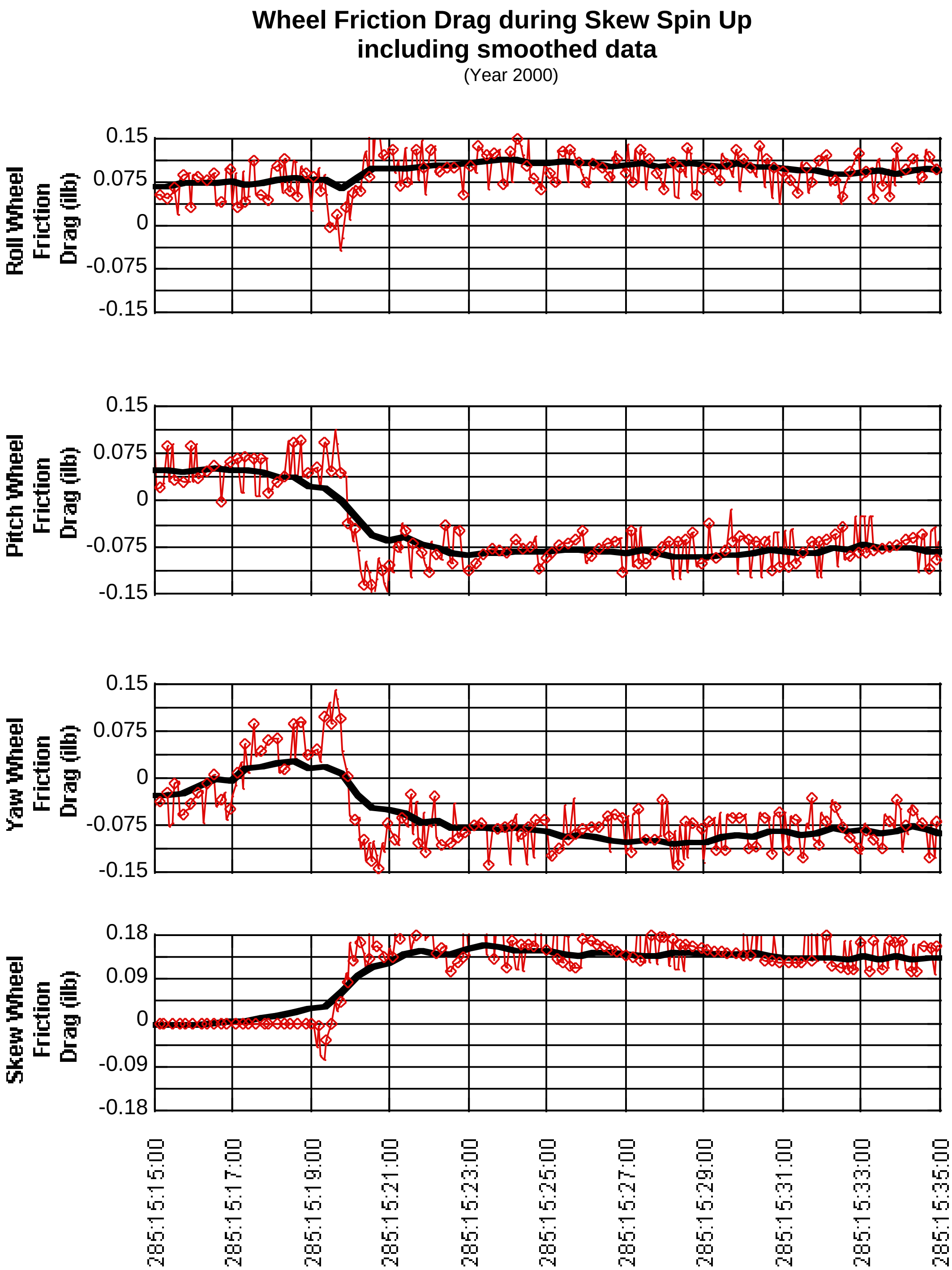


Figure 8 – Wheel Drag during Skew Spin up (Year 2000)

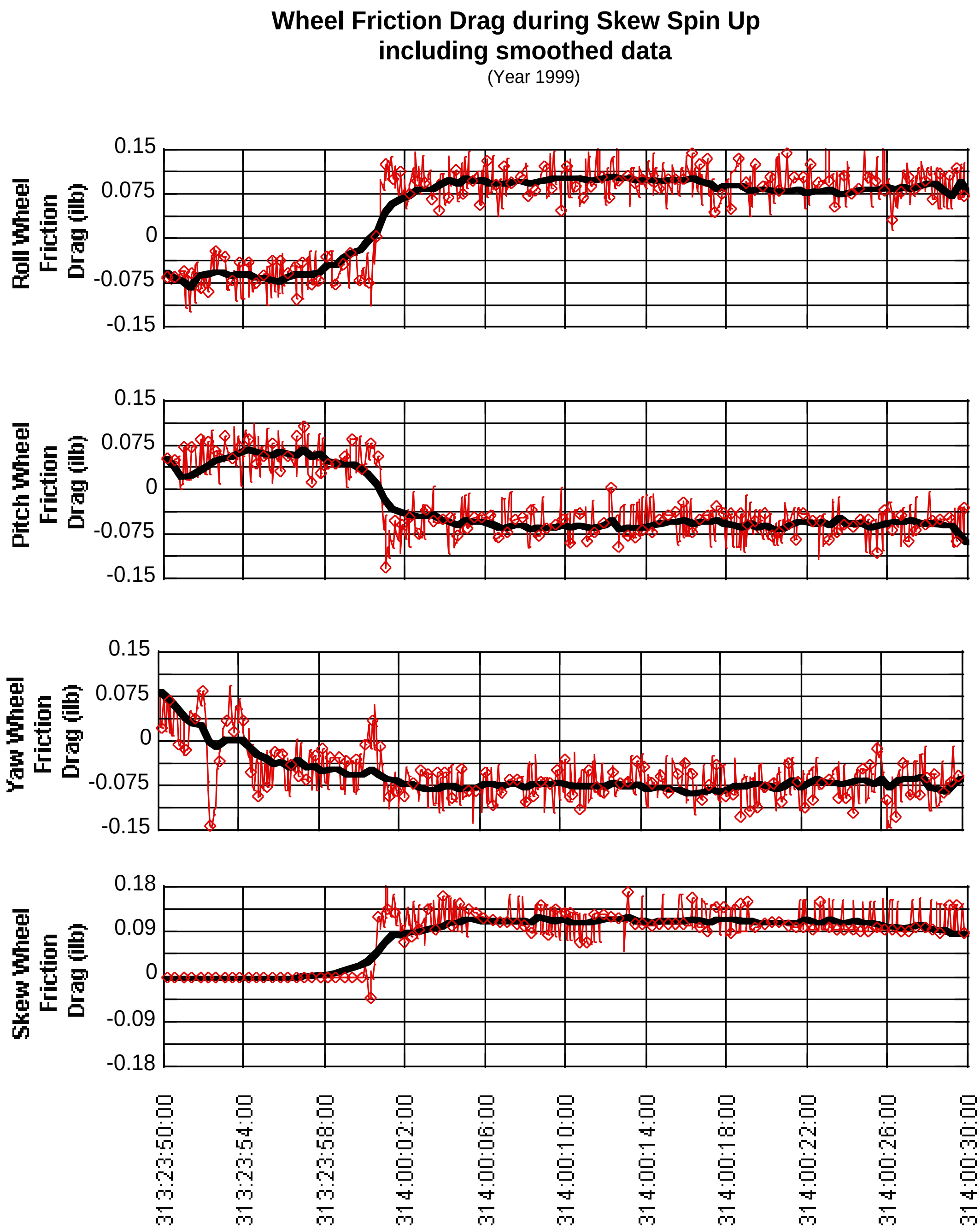


Figure 9 – Wheel Drag during Skew Spin up (Year 1999)

Transfer of wheel momentum during the skew spin down was smooth and **Figure 10** verifies the pickup of the wheel momentum in the spacecraft body momentum. The Roll axis shows the largest change in system momentum; a change of 20 in-lbs was noticed on this axis that corresponds to 1/12th the capacity of the reaction wheel (total 240 in-lbs). Both the Pitch and Yaw axis absorbed only 1/24th of the capacity of their reaction wheels and together, all wheels were kept well within their on-orbit intended operating range (±3000 RPMs).

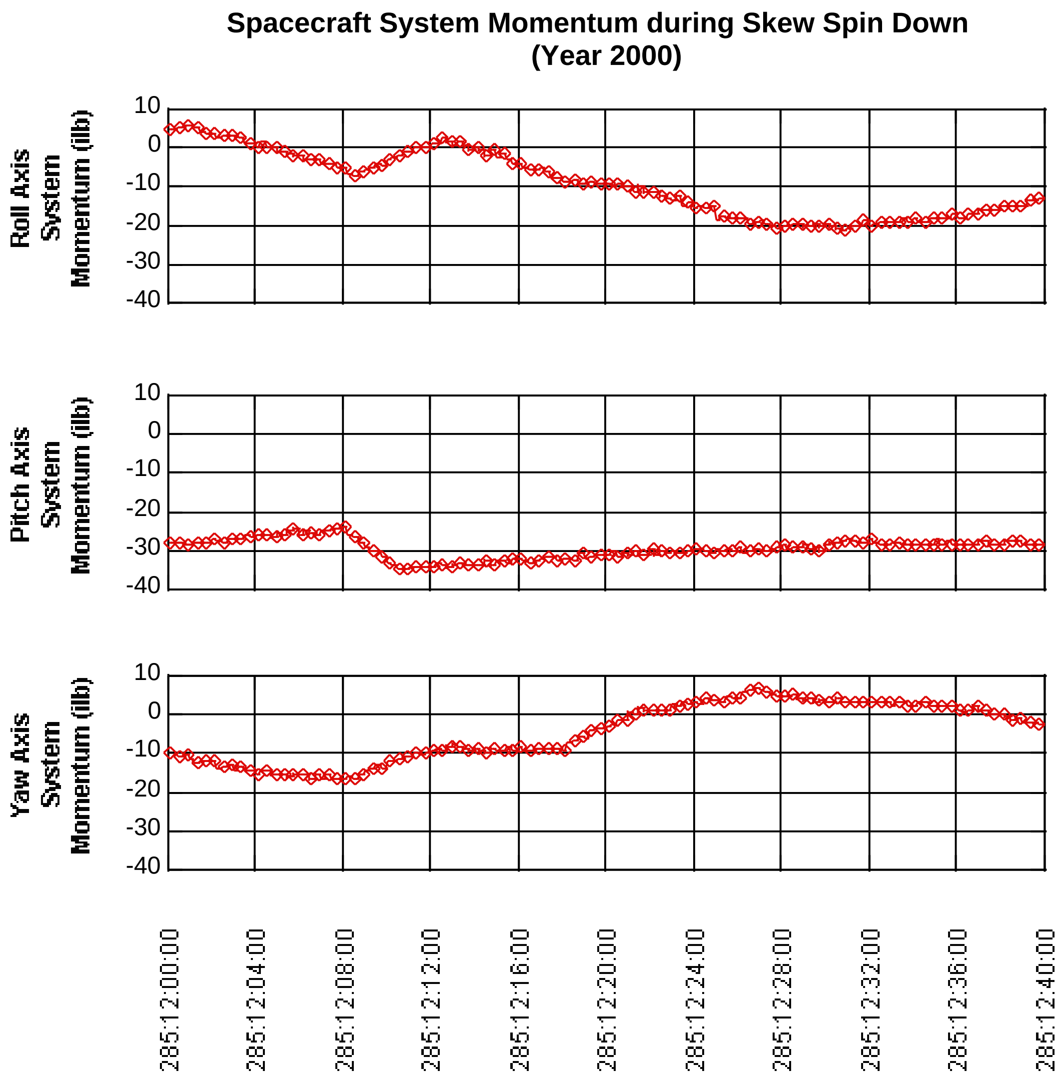


Figure 10 – Spacecraft System Momentum during Skew Spin down

Yaw Slews

The year 2000 Delta-i operation consisted of slewing out about the spacecraft yaw axis by +90.75 degrees, burning the Orbit Adjust jets for 19.5 minutes and slewing back by -90.75 degrees. This sequence of slew-burn-slew spanned 55 minutes which consisted of the following activities: a 13 minute 19 second slew to +90.75 degrees, followed by 3 minutes 47 seconds of settling, a 19 minute 32 second burn, followed by 5 minutes 24 seconds of settling, and a 13 minute 18 second –90.75 degree slew before retuning to near nominal attitude. **Figure 11** summarizes the various transitions of the ACS control mode during the Delta-i sequence. All ACS transitions were commanded via stored or ground commands, except for the transition from Maneuver to Precision which was done autonomously via FSW.

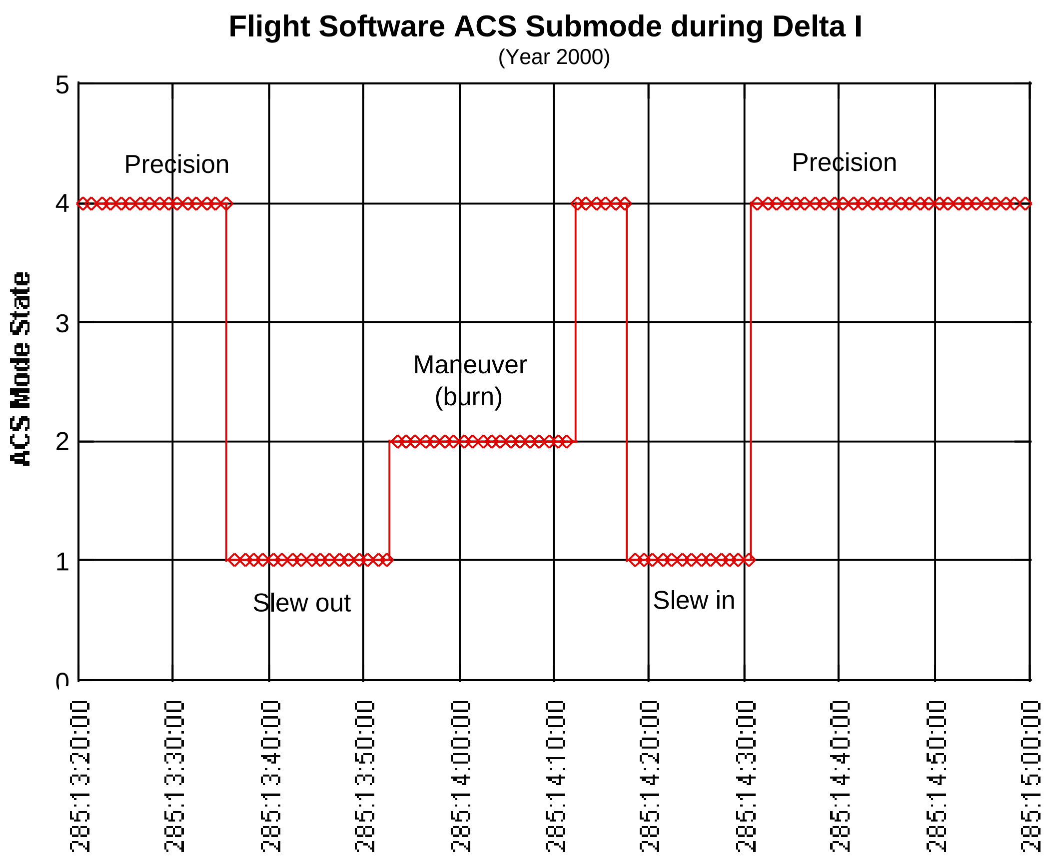


Figure 11 – ACS Submode during Delta-i

Figure 12 depicts the slew out activity in terms of controller Attitude and Rate errors, and the Earth Sensor Assembly (ESA) derived Yaw error. While in the SLEW control mode, the spacecraft was rotated about the Yaw axis by introducing a yaw attitude error into the FSW, with a maximum commanded slew rate of 0.125 deg/sec over an input period of 12 minutes 6 seconds (sequence: RTCS YAW_SLEW). The SLEW control law worked correctly to diminish the induced error, whose maximum yaw attitude error peaked at -5.25[1] degrees within 90 seconds of the command. At this time, a peak yaw rate error of -0.125 degrees/sec was registered. FSW correctly clamped the attitude error at -5.25 degrees and thereafter the residual error was used continually to drive the spacecraft out to its final destination.

The yaw error drifted below -4 degrees after the slew commanding was completed at 285/13:47:40, at which time the controller used the remaining yaw attitude error to “coast” to the intended target of +90.75 degrees. When the slew commands terminated, the yaw error once again increased rapidly consequently peaking the yaw rate error at +0.125 degrees/sec. After 1 minute and 13 seconds of coasting and driving beyond the null yaw error, a peak yaw attitude error of 1 degree was recorded. Subsequently another 3 minutes and 47 seconds elapsed, before all control errors and rates were finally settled out. During the period of minimal yaw attitude error increase, the yaw rate error was minimized to near zero.

Upon completion of the initial 90 degree Yaw slew, the roll rate was placed on the spacecraft Pitch axis and the orbit pitch rate was transferred onto the spacecraft Roll axis. **Figure 14** depicts the same activity for the case of the slew back from +90.75 degrees toward nominal attitude. In both slew instances, all Attitude and Rate error parameters were within specification.

([1]The FSW reports a negative in the attitude error upon slew out, as the actual attitude reference state lags behind the desired attitude reference state, which is being propagated forward.)

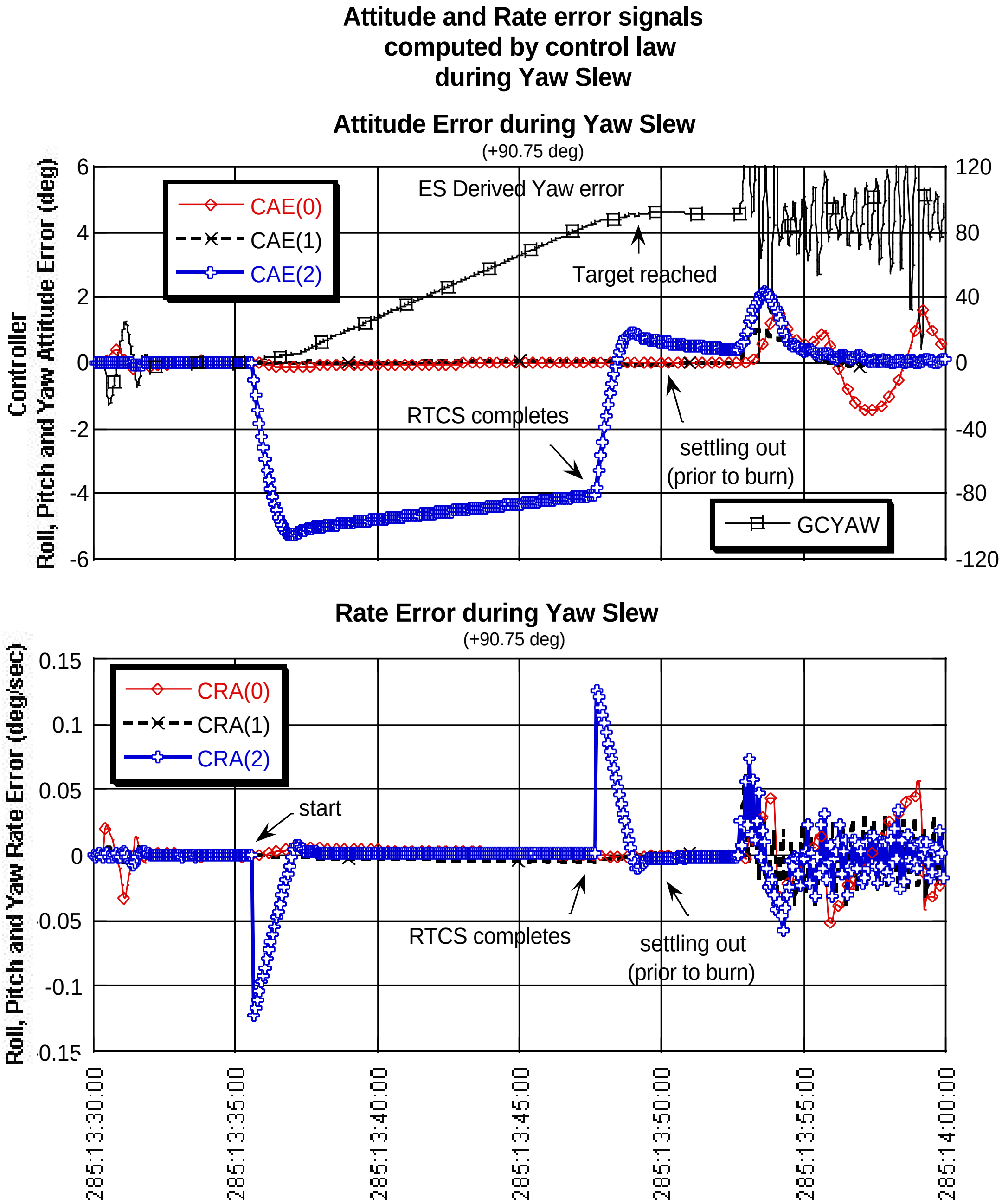


Figure 12 – Attitude and Rate Errors during Yaw out

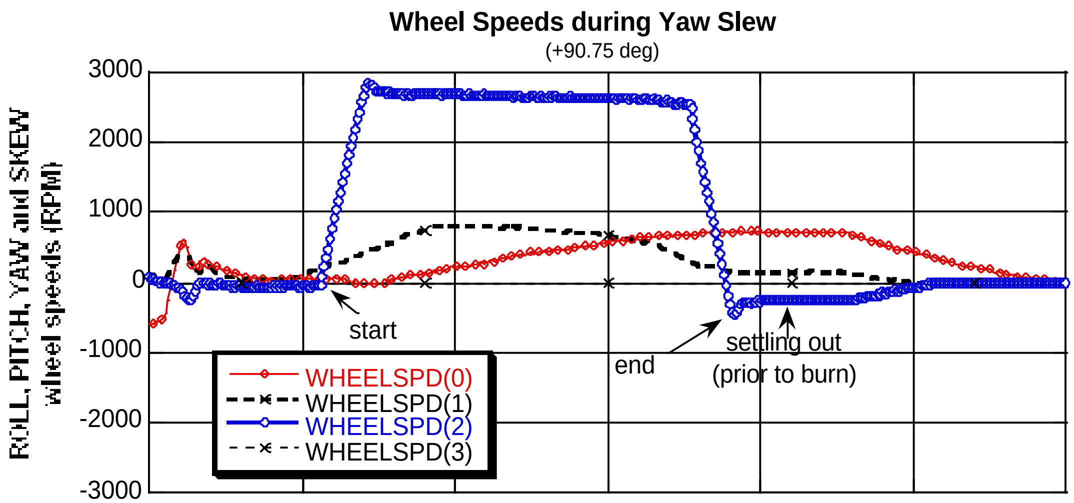
Figure 13 shows nominal wheel speeds and torque commands during the slew out to +90.75 degrees. The yaw wheel speed reached 2800 RPM within 90 seconds of the start of the slew and settled down to 2500 RPM prior to slew completion. The yaw wheel torque commands were peaked out at +256[2] counts upon start of slew and at -256 counts upon the end of slew. Each of these peaks were sustained for approximately 90 seconds during which time the wheels were being spun rapidly in either the forward or reverse direction.

As a comparison to wheel torque during a slew, other high torque events are shown in **Figures 13** and **15**, such as solar array start and stop, and thermal snap, which generate similar torque magnitudes but are sustained over a much shorter time span. More importantly, these figures show that at the start of the jet firings, the spacecraft wheel speeds had sufficient margin to execute thruster firings and stay within the wheel operating range of ±3000 RPM during the burn. The pitch wheel was at +137 RPM; the yaw at -254 RPM; the skew at 0 RPM; and roll at +725 RPM.

Figure 15 depicts nominal torque and wheel speed profiles for the slew back from +90.75 degrees. Pitch and Roll speeds can be seen “crossing over” on the return to nominal attitude, as the orbit rate is once again placed on the pitch axis and the spacecraft roll axis is positioned along the velocity vector. In all instances, Wheel Speeds and Torque Commands were as expected.

([2]For all wheels, the positive torque polarity denotes an increase in wheel speed while the negative polarity denotes a decrease in wheel speed.)

Wheel speed and torque commands issued during Yaw Slew



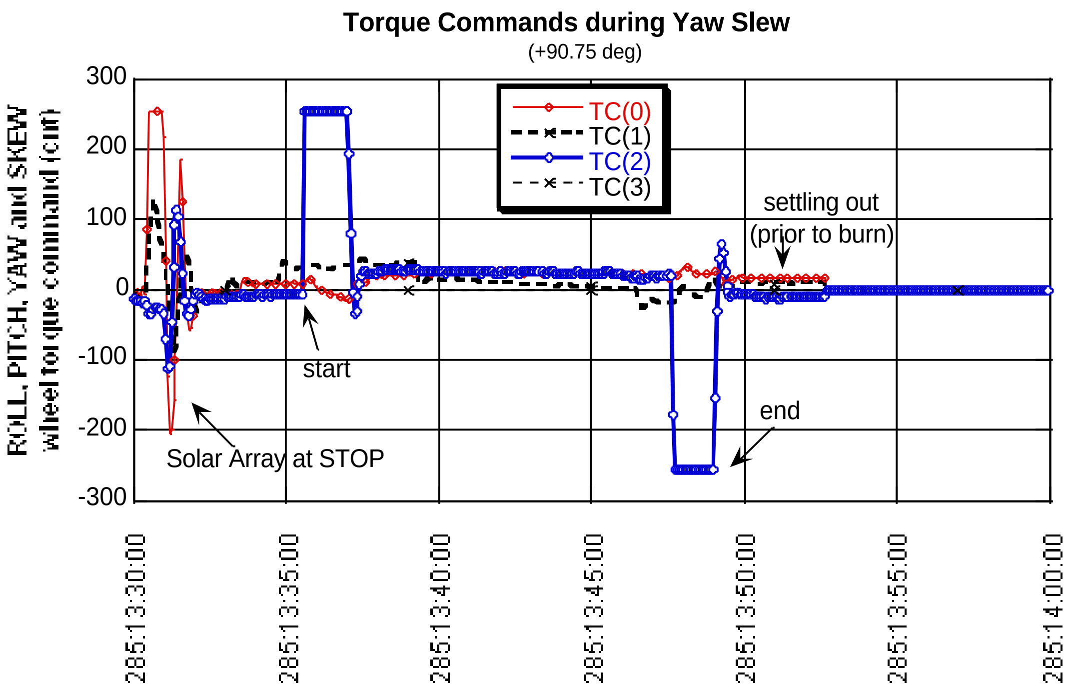


Figure 13 – Wheel activity during Yaw out

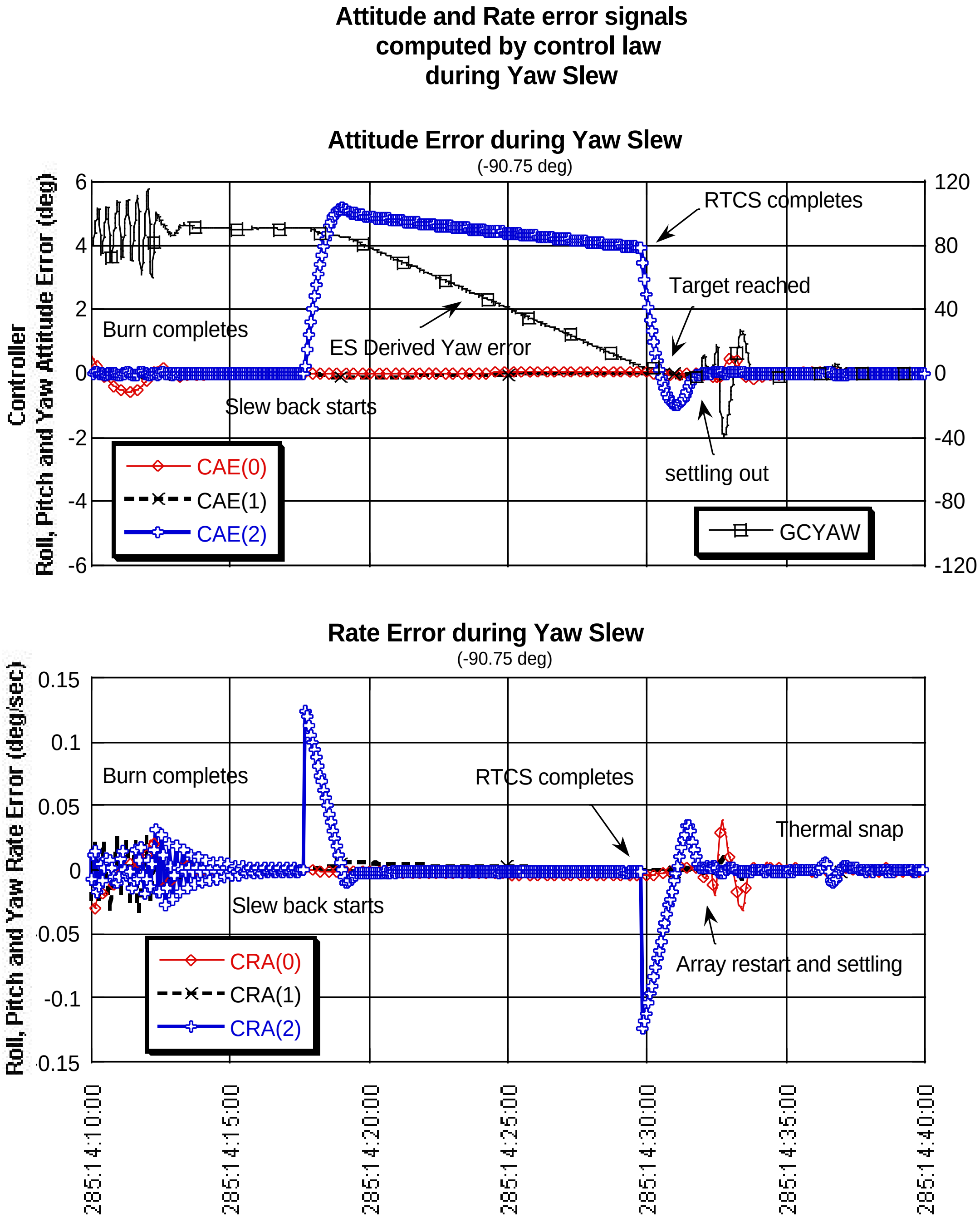


Figure 14 – Attitude and Rate Errors during Yaw back

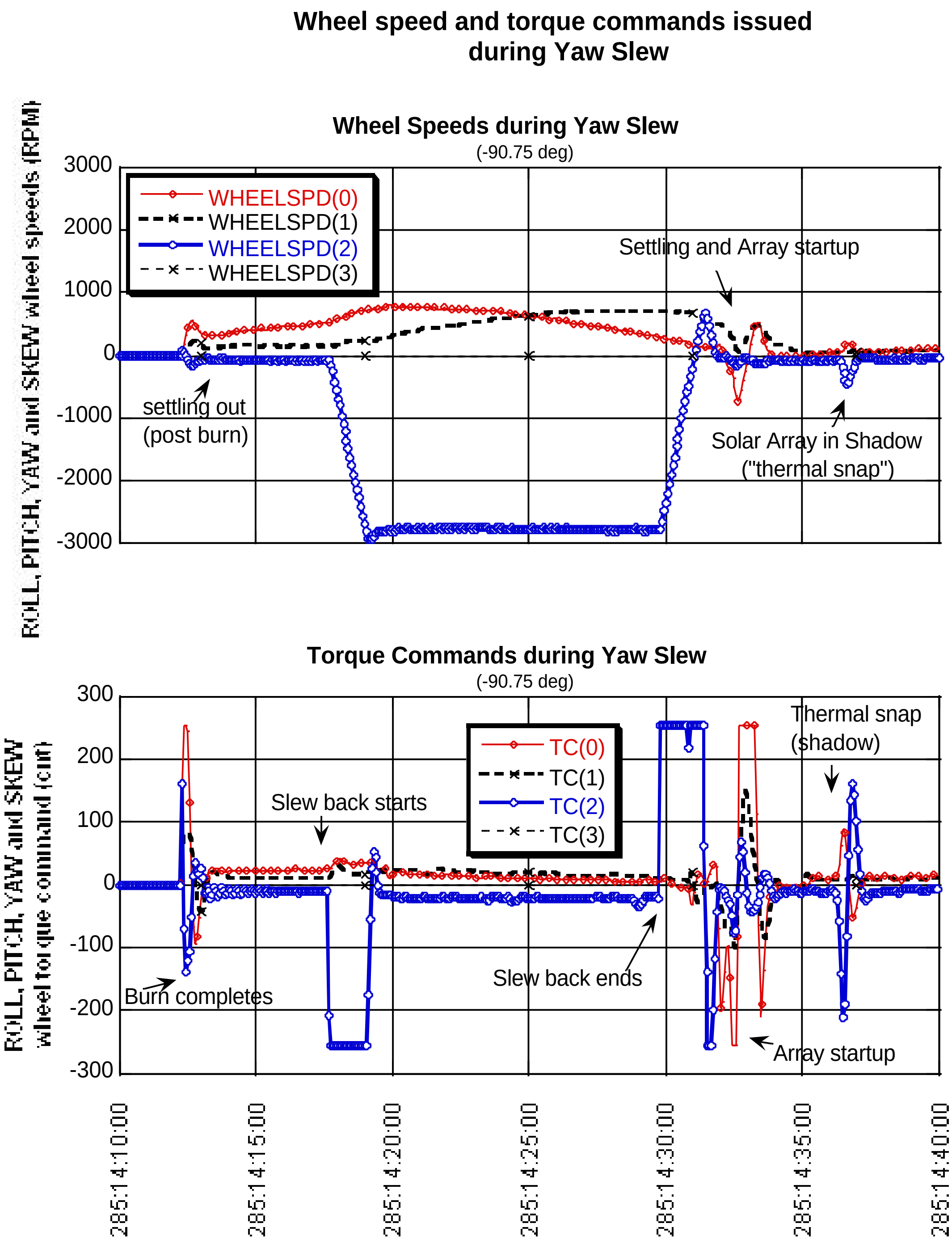


Figure 15 – Wheel activity during Yaw back

Burn

In order to prepare the spacecraft for the slew-burn-slew sequence, predeli and postdeli TSTOL procedures were used. In addition, two RTCSs were executed. A copy of the overall procedure is attached in Appendix B. Thruster configuration #1 was selected which uses jets 1-4 to provide the Delta-velocity thrust and also to control yaw and pitch attitude corrections. Roll attitude is controlled using jets 5-8. A perfect burn, one that requires no off-pulsing for pitch or yaw errors or pulsing of jets 5-8 for roll errors, would have resulted in jets 1-4 each reaching 10612 pulses, and 0 pulses on all other jets. During the 1172 second burn, the final number of pulses on each jet was as follows:

Jet	Pulses	Jet	Pulses
1	11184	5	0
2	11722	6	78
3	10040	7	0
4	9502	8	78

The jets are arranged on the spacecraft as shown in **Figure 16**.

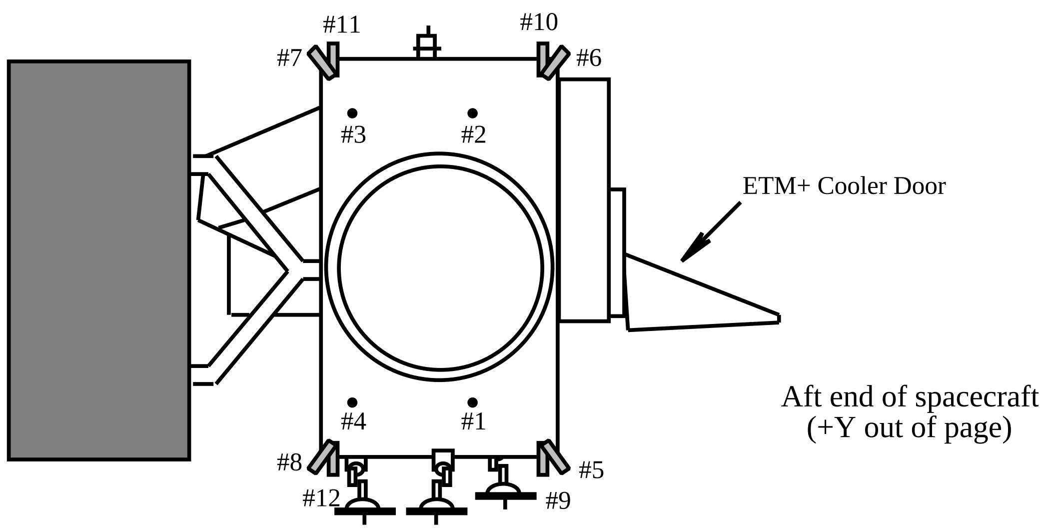


Figure 16 – Thruster Layout

Jets 6 and 8 fired in six different "groupings", each lasting approximately 10-15 pulses. These groupings were spread throughout the entire burn and were in response to a positive roll error and rate. The maximum roll error was +1.65°. The maximum roll rate was +0.056°/sec. Consistent with Delta-i #1, pitch and yaw axis both experienced positive errors at the start of the burn. The pitch error rose to +1.05° (very similar to delta-i #1) and was slowly reduced to near 0° within 3 mnutes. The yaw error rose to

+5.17° (nearly 3° higher than delta-i #1) and was reduced close to 0° in approximately 2 minutes. Maximum rates for pitch and yaw were +0.060°/sec and +0.13°/sec respetively. All RWAs were either at 0 RPM at the start of the burn, or drifted to 0 RPM within a few minutes of burn start. The roll RWA had the highest speed at the start of the burn (at +725 RPM) and drifted to 0 RPM within 8 minutes. Transition to Precision ACS mode occurs automatically upon completion of the burn and at that time, the wheels are again used to control attitude errors and rates. All RWAs reacted to residual rates and errors present at the end of the burn, but none of the wheels changed more than |1000| rpm.

As expected, during the burn, jet valve temperatures for jets 1-4 decreased due to the flow of cooler N_2H_4 through the lines. The valve temperatures dropped approximately 10° during the burn and reached steady state between 25 and 30°C. After the burn, the valves heated past their pre-burn temperatures due to "soak back" from the hot jets and topped out at approximately 45-55°C. Valves for jets 6 and 8 showed soak back heating during and after the burn and reached maximum temperatures similar to jets 1-4. Jets 5, 7, and 9-12 were not fired, but heated slightly due to orbital geometry. Catalyst bed temperatures rose in jets 1-4 to values ranging from 521° to 539° during the burn. These maximum temperatures are nearly identical to those seen in delta-i #1 despite the large difference in burn duration. Catbed temperatures for 6 and 8 also rose and were consistent with the number of pulses each experienced.

Wheel Behavior during Thruster Firings

During the 2000 Delta-i all four wheels reached 0 RPM. Wheels are not commanded by FSW during Maneuver mode and begin "coasting" towards 0 RPM immediately upon entering that mode. A comparative history of wheel spindown during the past Delta-i burns is shown below. After reaching 0 RPM, the wheels remain there until the burn completes and Precision mode is automatically entered.

	1999		2000	
Wheel	At Burn Start	Time to 0RPM	At Burn Start	Time to 0RPM
Roll	692 RPM	N/A	704 RPM	12 min
Pitch	254 RPM	4 min	147 RPM	3 min
Yaw	-336 RPM	4.5 min	-272 RPM	4 min

Figures 17-20 show wheel rates and momentum for both the 2000 and 1999 burns.

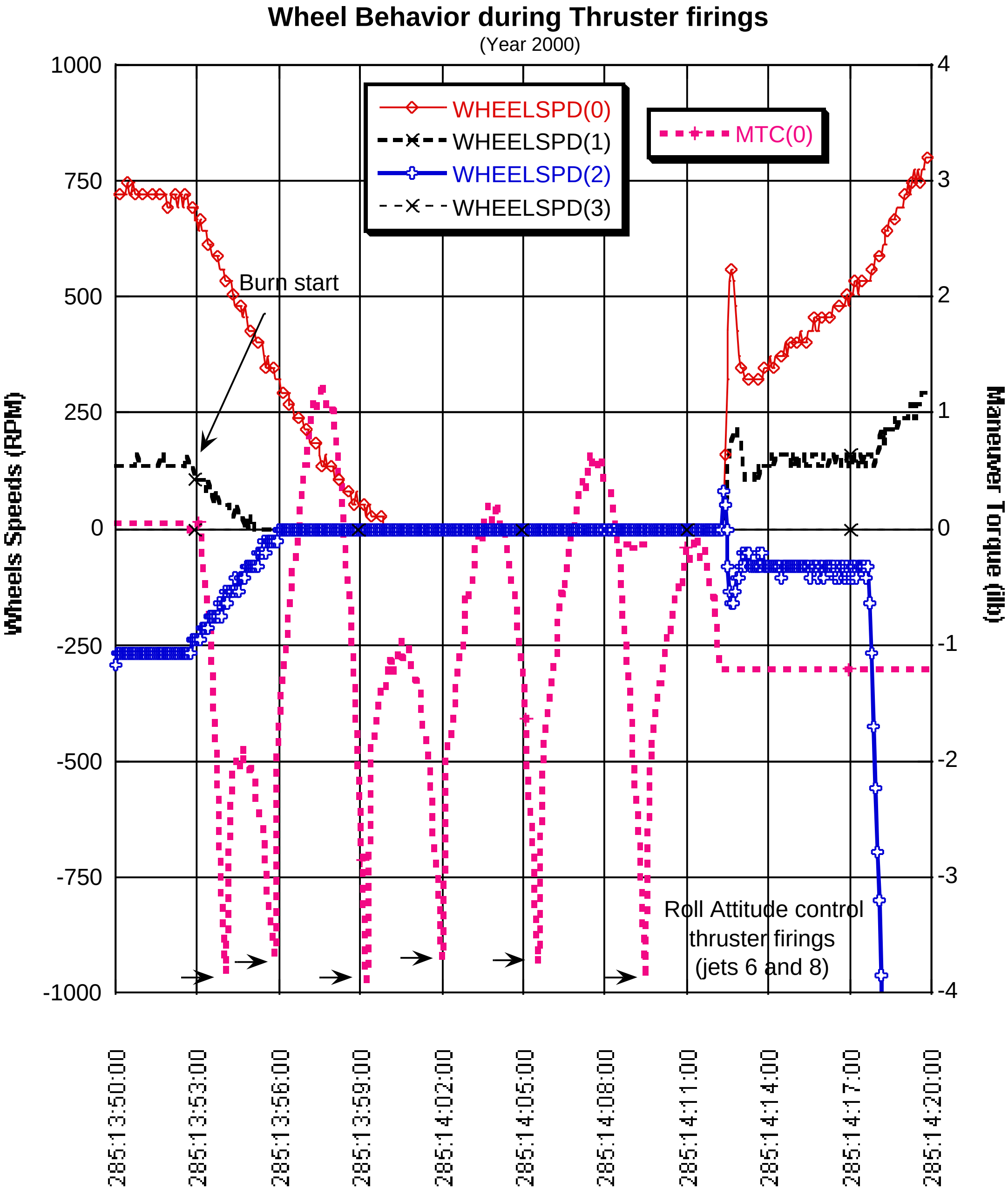


Figure 17 – Wheel 0 RPM Profile during Thruster firing (year 2000)

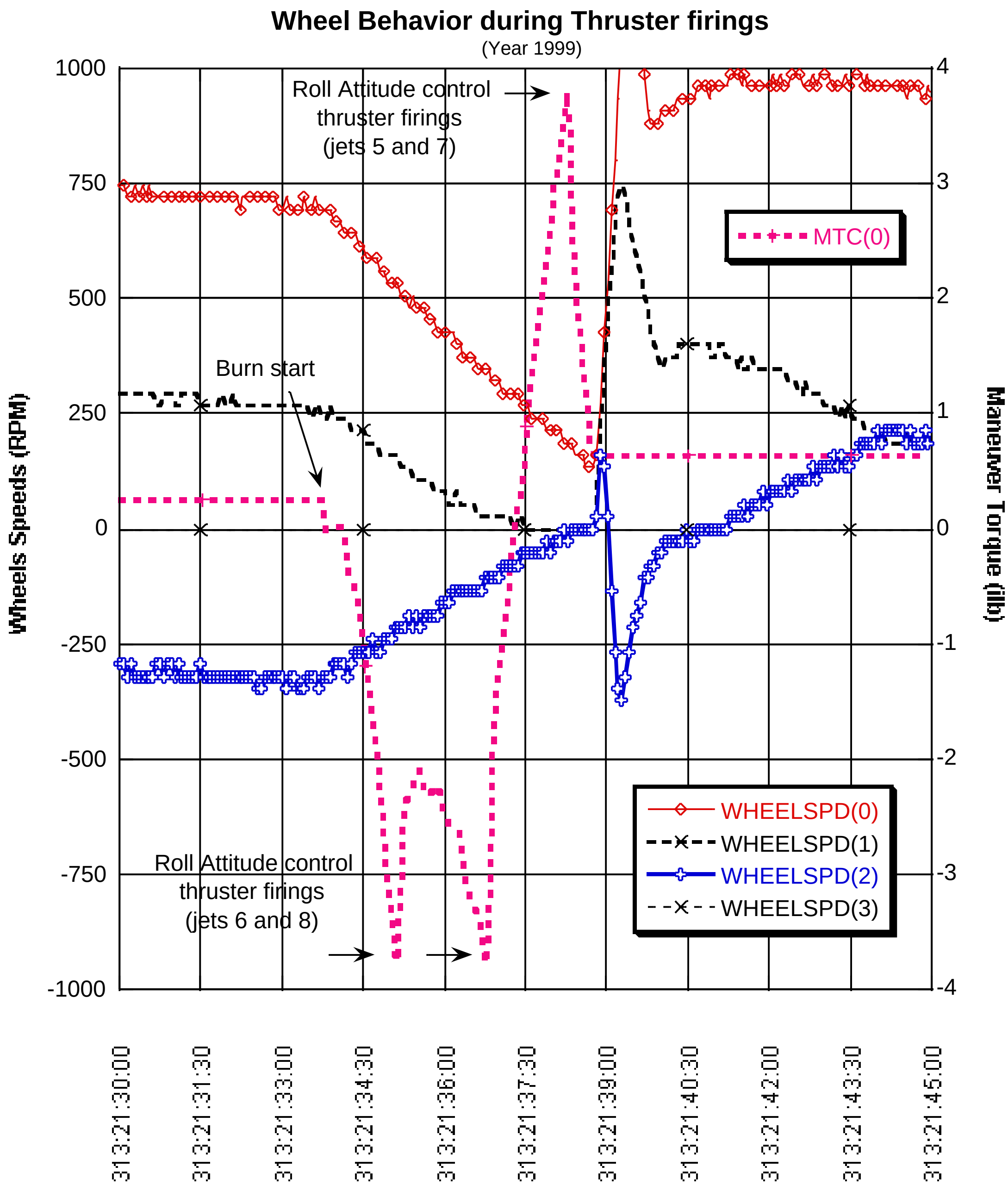


Figure 18 – Wheel 0 RPM Profile during Thruster firing (year 1999)

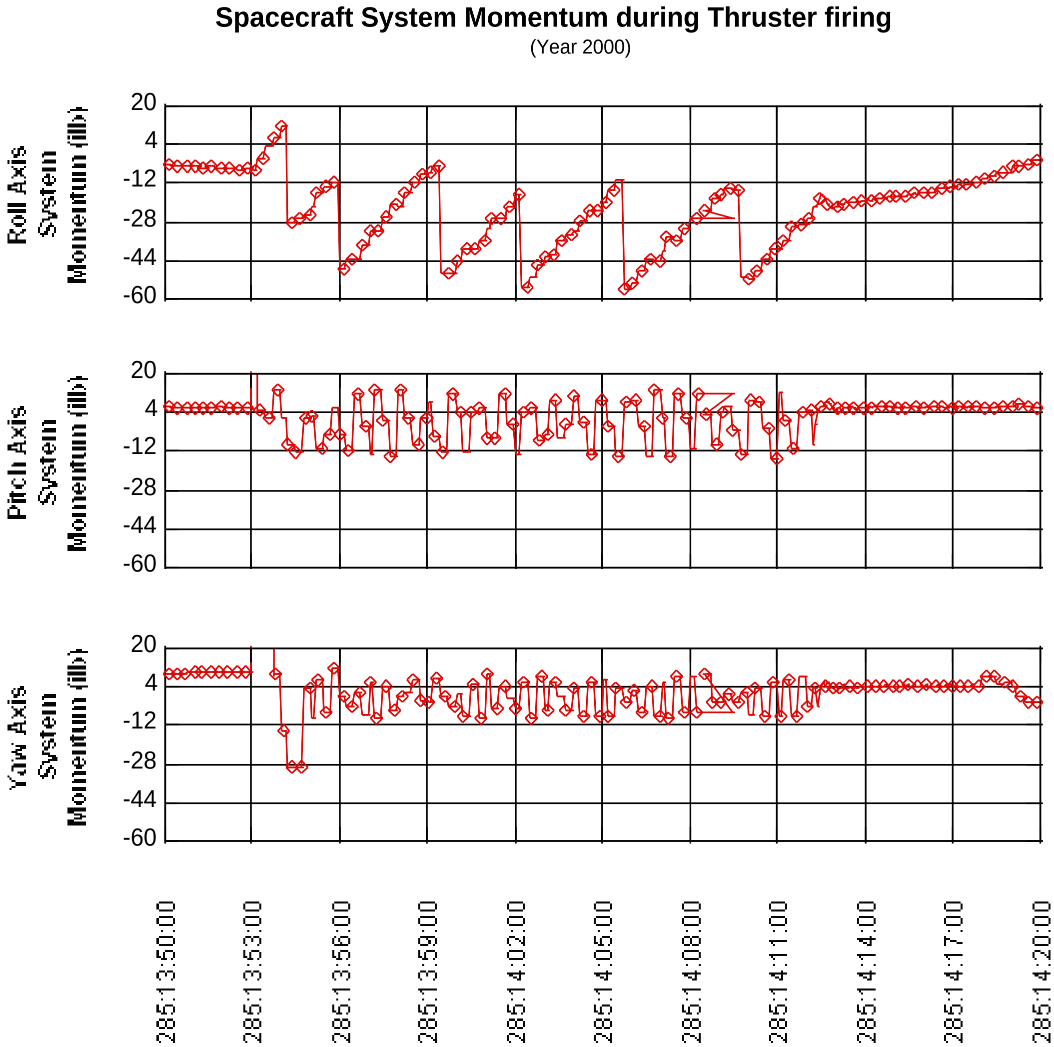


Figure 19 – Spacecraft System Momentum during Thruster firing (year 2000)

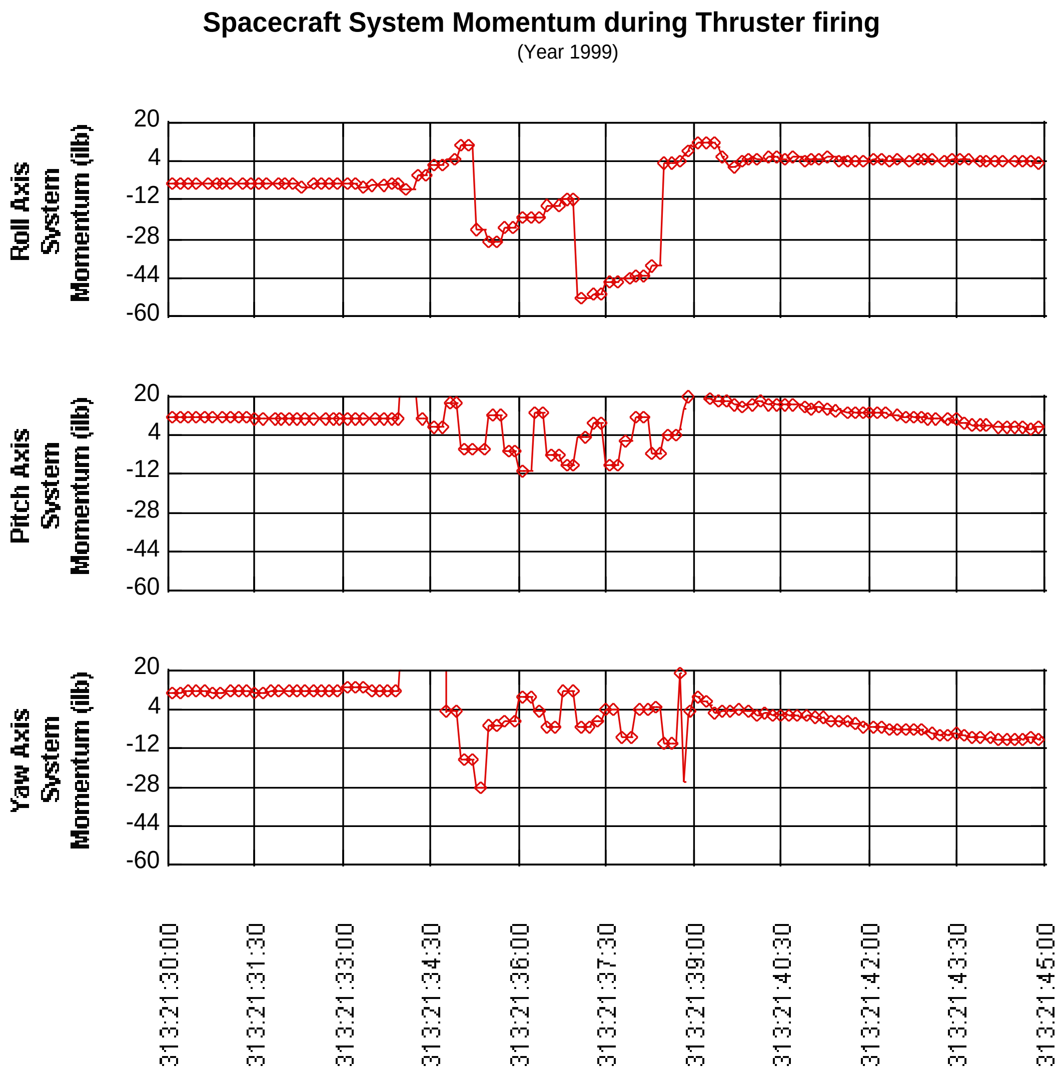


Figure 20 – Spacecraft System Momentum during Thruster firing (year 1999)

Abort Criteria Decision

When performing a Delta-i sequence, the FSW ACS mode is switched from the normal PRECISION mode through the SLEW and MANUEVER modes (see **Figure 11**). These latter modes relax the attitude and rate error abort limit thresholds which are used to terminate the SLEW or MANEUVER if a violation is detected during the Delta-i operation. During the 5 minute Delta-i sequence of 1999, an attitude error approaching the abort criteria (-2.65 degrees) was noted while in the MANEUVER mode. During planning meetings for the 2000 Delta-i, a concern was raised about the longer MANEUVER duration (19 minute burn) allowing the default attitude abort criteria to be violated. To ensure completion of the 2000 thruster burn, the precaution was taken to permanently increase the attitude abort criteria (to ±5.5 degrees) within FSW for

MANEUVER mode. The MANUEVER abort criteria is summarized in **Table 1** and the attitude and rate errors experienced during the 2000 Delta-i thruster firing are summarized in **Table 2**.

Attitude Error (deg)	**Default**	**New**
Roll	±3	±5.5
Pitch	±3	±5.5
Yaw	Not checked	Not checked
Rate Error (deg/sec)	**Default**	**New**
Roll	±0.22	±0.22
Pitch	±0.22	±0.22
Yaw	±0.22	±0.22

Table 1 - MANEUVER mode Abort Thresholds

Attitude Error (deg)	**1999 Max/Min**	**2000 Max/Min**
Roll	+1.65 / **-2.65**	+1.65 / **-1.47**
Pitch	+1.03 / -0.18	+1.05 / -0.54
Yaw	Not checked	Not checked
Rate Error (deg/sec)	**1999 Max/Min**	**2000 Max/Min**
Roll	+0.06 / -0.06	+0.06 / -0.05
Pitch	+0.07 / -0.04	+0.06 / -0.04
Yaw	+0.12 / -0.13	+0.13 / -0.12

Table 2 – Attitude and Rate performance between 1999 and 2000 Delta-i's

Roll Axis Control during Maneuver mode

Figures 21 and **22** profile the Attitude and Rate Error signals during thruster firing, and the resulting Maneuver Torque Command (MTC) generated to control the spacecraft during the burn. The maneuver thruster control torque is the sum of the product of proportional gain and control attitude angle (CAE) PLUS the product of rate gain and control attitude rate error (CRA) PLUS the attitude integral term. The MTC term is therefore directly used to determine the pulse width size for all thruster firings. Given that thruster configuration 1 was chosen for the burn, jets 5-8 were used to control the Roll axis. The negative value of MTC(0) in **Figure 21** determines that jets 6 and 8 are used to control excessive positive Roll Attitude error. **Figure 21** shows the relationship between attitude error and MTC; and indirectly, the results of jets 6 and 8 firing. **Figures 21** and **22** show that at the combination of positive Roll Attitude and Rate error (and the integral term), the roll MTC term reaches a minimum value at which time jets 6 and 8 are fired. This then corrects for the Roll Attitude error (with an added spike in Roll Rate), until the next set of circumstances in attitude and rate error necessitate another jet firing. During the Roll Attitude thruster firings, a total of 6 “off pulse” cycles using OAE jets were observed. In the case where MTC(0) had been positive, jets 5 and 7 would have fired in response to a negative Roll Attitude and Rate error. The persistent positive error and rates in the Roll axis may be linked, at least partially, to the Roll wheel spindown from a value of nearly 750 to 0 RPM during the first few minutes of the burn. During the 19.5 minutes of thruster firing, all jets were commanded by FSW as expected.

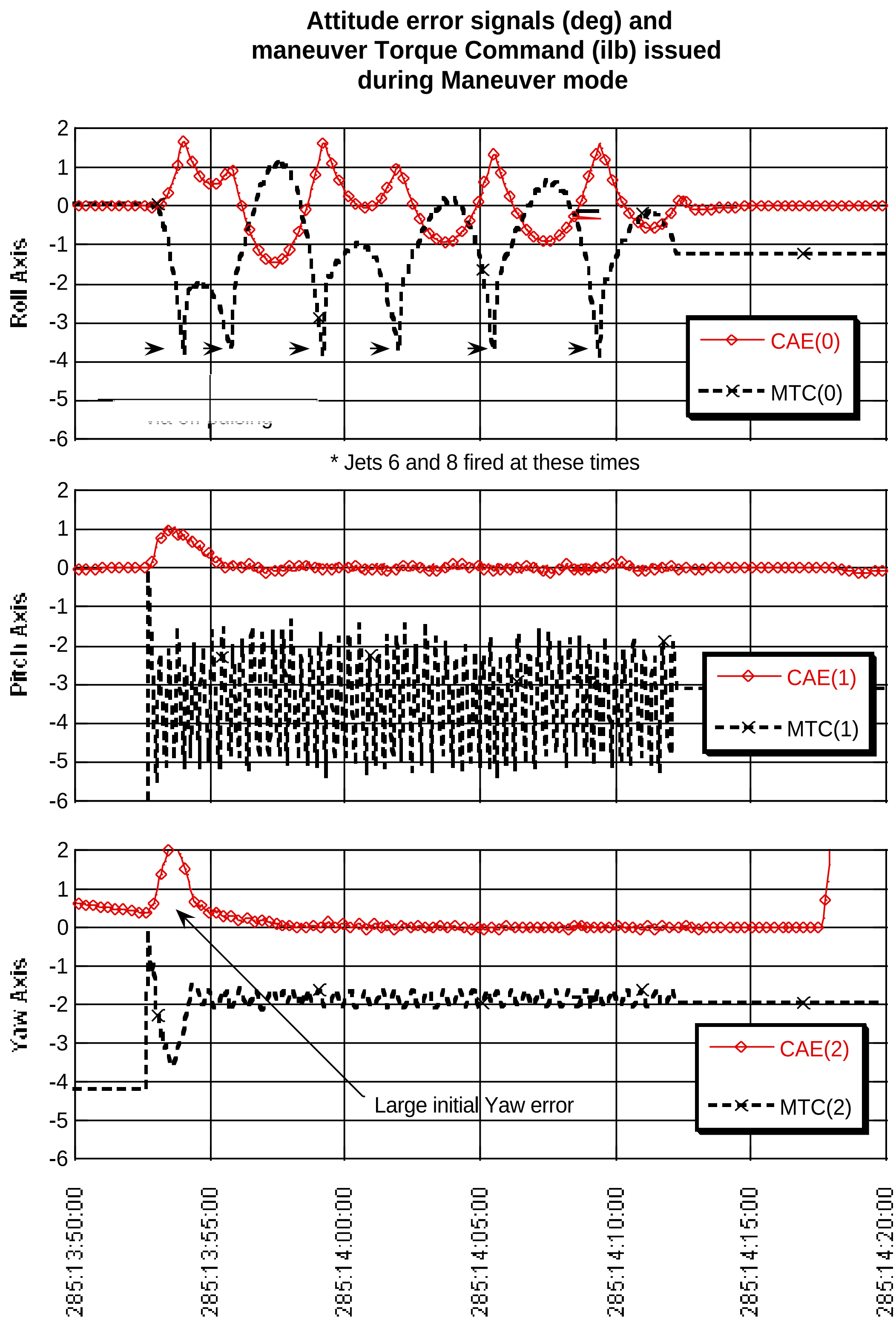


Figure 21 –Attitude Control during Maneuver mode

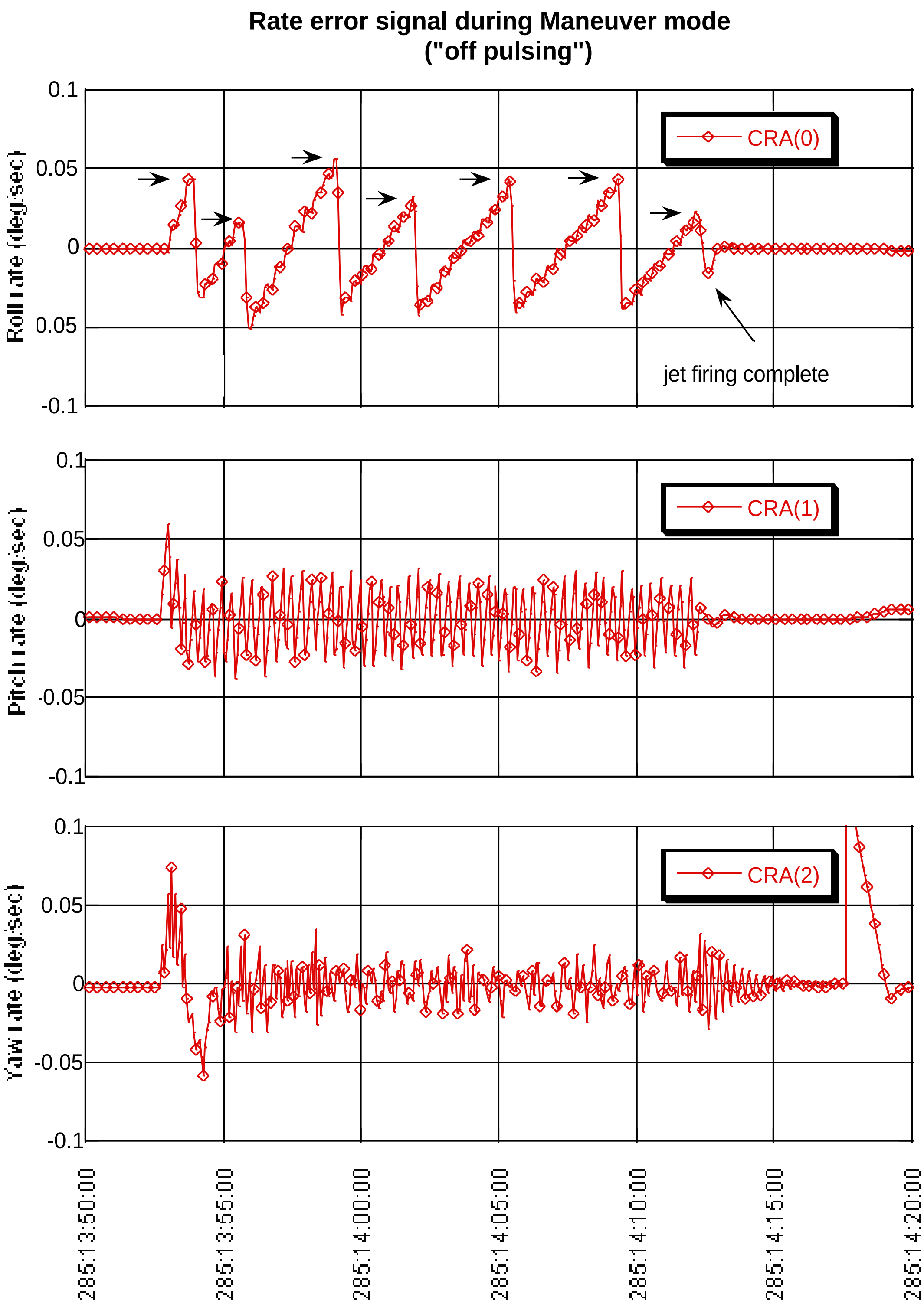


Figure 22 – Rate Errors experienced during Maneuver mode

PRADS/Precision – Post burn

Background

In order to preserve the established attitude knowledge prior to a Delta-i, the on board star processing and precision attitude determination software (PRADS) is disabled during the two commanded slews and the burn. The purpose of shutting down this software is to prevent attitude knowledge from being adversely perturbed via the acceptance of unqualified star transits during the slew-burn-slew process. However, due to the allowance of uncorrected gyro drift and unknown gyro misalignments in the transformed system, the attitude knowledge will be altered prior to reinitiation of the PRADS software.

As a prelude to shutting down the PRADS star processing software in 1999, several experimental runs were executed on LSIM to determine the impact on the precision attitude reference after completion of a Delta-i sequence. The insight gained during this time period convinced the FOT and LMMS Engineering support that uncorrected gyro drift and uncalibrated (misaligned) gyros could combine to embellish the pre Delta-i attitude solution and lead to erroneous star identifications upon return to star processing. This would lead to divergence from the precision attitude state and reconvergence of the Kalman filter.

In 1999, upon completion of the Delta-i, the return to star processing led to identification of several erroneous stars and 3 resets of PRADS before the PRADS solution was restored. Stemmimg from this experience the 2000 Delta-i started with realigned celestial sensor assembly (CSA) slit normal geometry, (in an effort to improve star identification performance) and with the original gyro alignment values. A gyro calibration procedure (offset slews) was performed on the spacecraft in mid 2000 and several LSIM runs were performed in an attempt to validate the gyro calibration solution. However, due to a lack of time and consensus, updated gyro alignment values were not updated in FSW prior to the 2000 Delta-i. As a result, the consideration for PRADS convergence in 2000 was placed on returning to star processing or resetting of the software during a predicted time of **singularly unique, high quality star transits.**

When slewed out, the gyro roll and pitch inputs are interchanged. The orbit rate sensed by pitch during normal orientation is applied to the Roll axis and the roll rate instability is inputted into the Pitch axis. When the Delta-i sequence is complete, each of these axes will contain accumulated errors due to the combination of gyro misalignment and uncorrected gyro drift. The Pitch axis having sensed the perturbations caused by the roll attitude control thruster firings, contains the largest built up error.

Attitude Build Up

During the 2000 Delta-i sequence, as a consequence of disabling PRADS software for 56 minutes 27 seconds (starting at 285-13:34:44), uncorrected attitude errors were allowed to accumulate in the attitude control system. The same occurred in 1999 when the software was disabled for 47 minutes and 9 seconds, and the pitch attitude error grew from a pre-slew value of -0.10 degrees to a post slew value of -0.25 degrees (a -0.15 degree difference). In 2000, the pitch attitude error grew from a pre-slew value of 0.07 degrees to a post slew value of -0.39 degrees (a 0.46 degree difference). **Figures 23** and **24** show the attitude transients pre and post Delta-i for the 2000 and 1999 Delta-i's. The Earth Sensor Assembly (ESA) derived attitude is shown here, as it is an independent measure of the attitude state. The higher error in 2000 is a consequence of the longer PRADS shutdown and the roll thruster corrections. The roll error was very stable with a pre Delta-i value of -0.12 degrees and a post Delta-i value of -0.20 degrees.

Star Processing

In order to "reconverge" the PRADS filter, the FOT found that an area in the orbit that had several "good" stars in it was more important than an area that had many stars in it (quality, not quantity). "Good" stars were determined by experience over on orbit life with the star and star transit predictions. The Star prediction tool used prior to the 2000 Delta-i was instrumental in choosing the time to re-enable star processing (it is disabled during the slew-burn-slew sequence). Experience from the 1999 Delta-i showed that partial PRADS resets were not helpful and that, if necessary, only a Full reset should be tried. One full reset of the filter was used in 2000 (timed just prior to arrival at some "good" stars, but not near the terminator) and PRADS convergence occurred very quickly. A timeline of the PRADS recovery is shown below in **Tables 3** and **4**. PRADS never went "NOT COMPLETE". **Figures 25-27** show attitude and gyro information during the PRADS recovery.

Timeline of PRADS Recovery

Transit Time (predicted)	Star ID	Slit	Transit Time (telemetry)	Star ID	Slit	Transit Number
285/13:34:10	86	5	285-13:34:11	86	5	**7092 (last update)**
			285-14:31:11			PRADS Re-enabled
285/14:31:18	100	1	285-14:31:12	N/A	1	Not accepted
285/14:31:43	100	2	285-14:31:44	N/A	2	LOST/No match found
285/14:32:08	100	3	285-14:32:16	N/A	3	LOST/No match found
285/14:32:58	3500097	1	No transit			
285/14:33:36	3500097	2	No transit			
285/14:33:37	3420118	1	No transit			
285/14:33:49	3190085	6	No transit			
285/14:34:01	3370016	1	No transit			
285/14:34:08	3370016	2	No transit			
285/14:34:14	3500097	3	No transit			
285/14:34:15	3370016	3	No transit			
285/14:34:22	3420118	2	No transit			
285/14:34:28	3190085	5	No transit			
285/14:35:07	3190085	4	No transit			
285/14:35:08	3420118	3	No transit			
285/14:35:18	67	6	285-14:35:28	N/A	6	LOST/No match found
285/14:36:02	67	5	285-14:36:00	N/A	5	LOST/No match found
285/14:36:46	67	4	285-14:36:48	N/A	4	LOST/No match found
285/14:38:19	2490015	1	No transit			
285/14:38:20	2490015	2	No transit			
285/14:38:22	2490015	3	No transit			
285/14:42:19	1560096	6	No transit			
285/14:42:52	49	6	285-14:42:56	N/A	6	LOST/No match found
285/14:42:57	1590127	6	No transit			
285/14:43:07	1560096	5	No transit			
285/14:43:26	49	5	285-14:43:28	N/A	5	LOST/No match found
285/14:43:31	1590127	5	No transit			
285/14:43:54	1560096	4	No transit			
285/14:44:00	49	4	285-14:44:00	N/A	4	LOST/No match found
285/14:44:04	1590127	4	No transit			
285/14:44:06	2080103	1	No transit			
285/14:44:08	2080103	2	No transit			
285/14:44:11	2080103	3	No transit			
			285-14:44:46			PRADS Reset

Table 3 - Timeline of PRADS Recovery (from Reenable to Reset)

Timeline of PRADS Recovery

Transit Time (predicted)	**Star ID**	Slit	**Transit Time (telemetry)**	Star ID	Slit	**Transit Number**
285/14:45:25	40	5	285-14:45:25	40	5	7093
285/14:46:15	40	4	No transit			
285/14:46:45	42	6	285-14:46:45	42	6	LOST/Multiple
285/14:46:57	42	5	No transit			
285/14:47:01	50	1	285-14:46:58	50	1	7094
285/14:47:10	42	4	285-14:47:12	42	4	LOST/Multiple
285/14:47:19	50	2	285-14:47:20	50	2	7095
285/14:47:38	50	3	285-14:47:39	50	3	7096
285/14:48:01	2030092	1	No transit			
285/14:48:19	1450129	6	No transit			
285/14:48:33	1450129	5	No transit			
285/14:48:44	2030092	2	No transit			
285/14:48:46	1450129	4	No transit			
285/14:48:59	1420114	6	No transit			
285/14:49:16	1420114	5	No transit			
285/14:49:26	2030092	3	No transit			
285/14:49:33	1420114	4	No transit			
285/14:50:13	2020014	1	No transit			
285/14:50:55	1530081	1	No transit			
285/14:51:08	2020014	2	No transit			
285/14:51:23	1530081	2	No transit			
285/14:51:52	1530081	3	No transit			
285/14:52:01	1300029	6	No transit			
285/14:52:03	2020014	3	No transit			
285/14:52:13	39	6	285-14:52:14*	39*	6	7097
285/14:52:17	39	5	285-14:52:18*	39*	5*	7098
285/14:52:21	39	4	285-14:52:22	39	4	7099
285/14:52:36	1300029	5	No transit			
285/14:53:10	1300029	4	No transit			
285/14:53:18	1450041	1	285-14:53:20*	N/A	1	LOST/No match found
285/14:53:29	1450041	2	No transit			
285/14:53:40	1450041	3	No transit			
285/14:55:09	36	6	285-14:55:09	36	6	7100
285/14:55:34	36	5	285-14:55:35	36	5	7101
285/14:55:42	1570059	1	No transit			
285/14:56:00	36	4	285-14:56:00	36	4	7102

Table 4 - Timeline of PRADS Recovery (from Reset to Recovery)

* Complete telemetry records indicating these values are not reported by FSW; however it is inferred from the prediction and the total number of stars accepted during this time period the identity and time of these “hidden” stars.

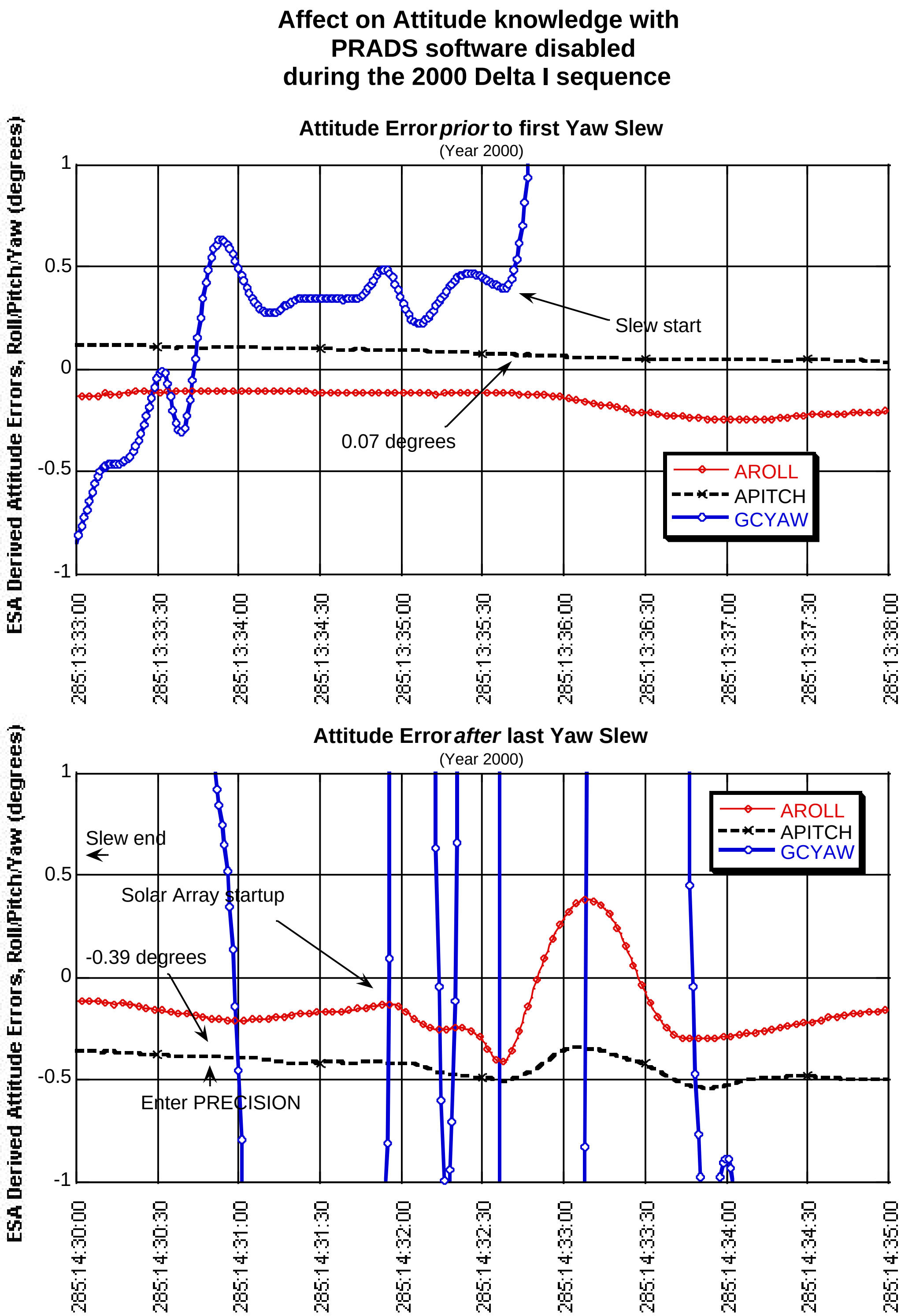


Figure 23 – Attitude Errors pre and post Delta-i (year 2000)

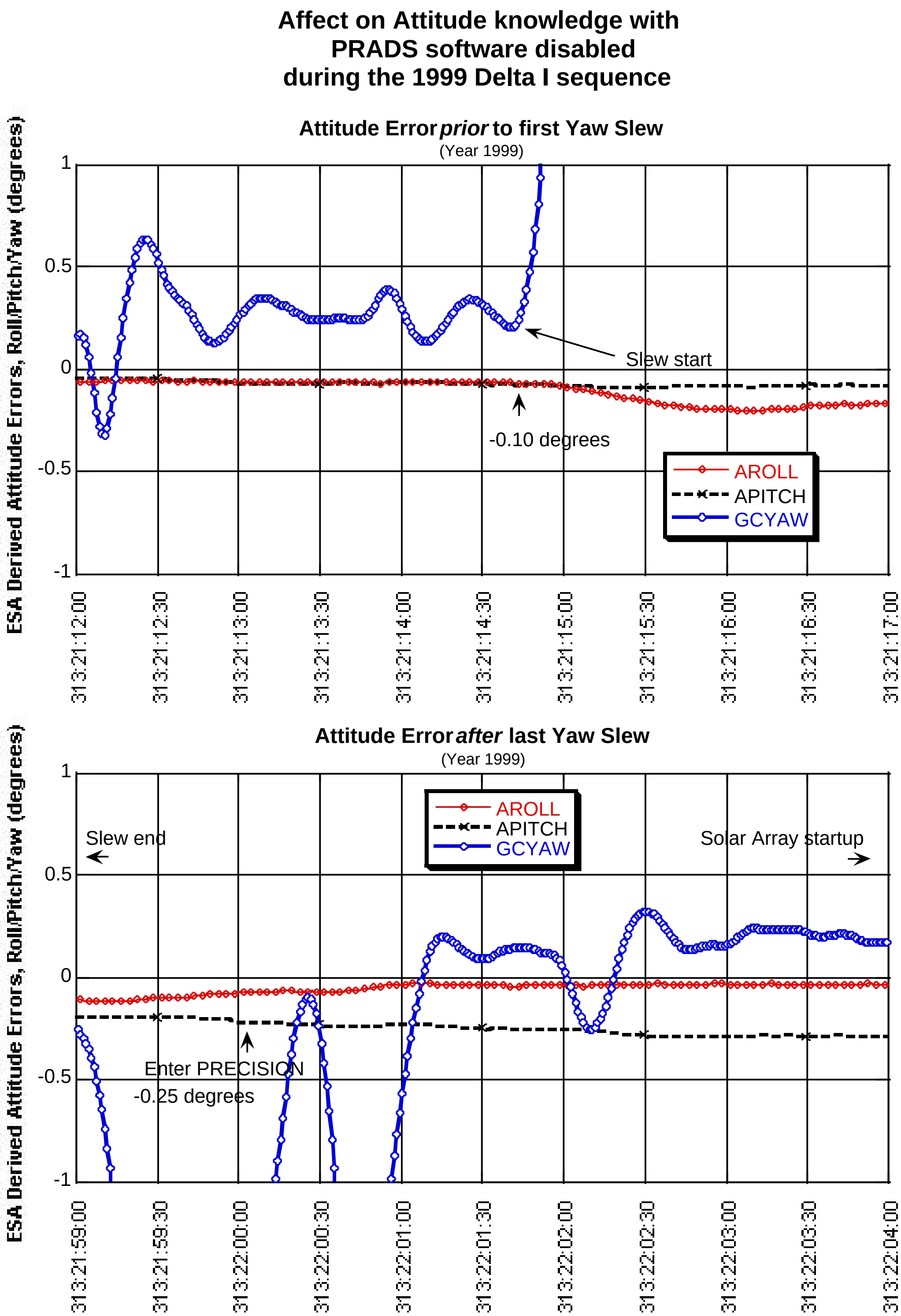


Figure 24 – Attitude Errors pre and post Delta-i (year 1999)

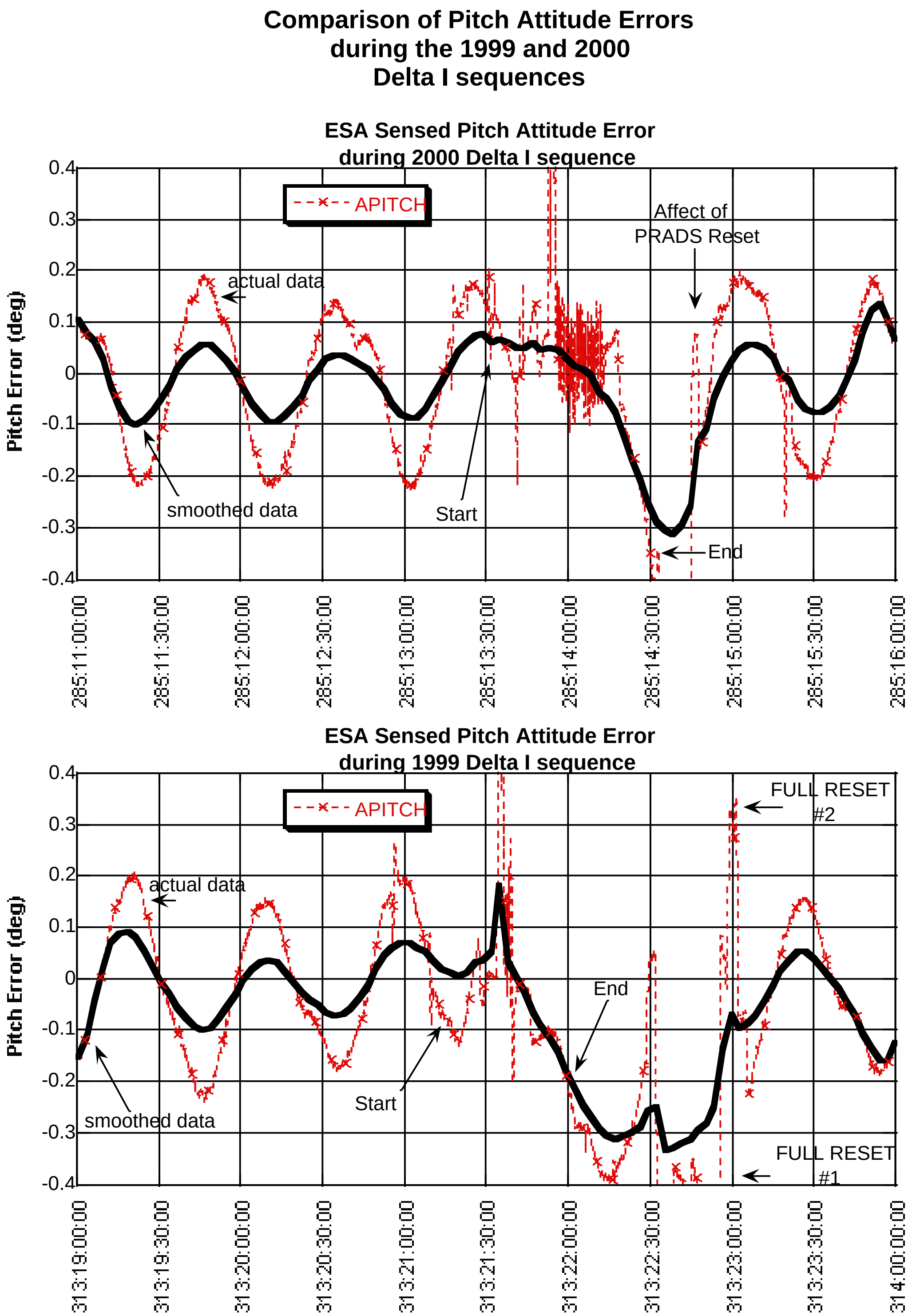


Figure 25 – Delta-i Attitude Error profile (1999 and 2000)

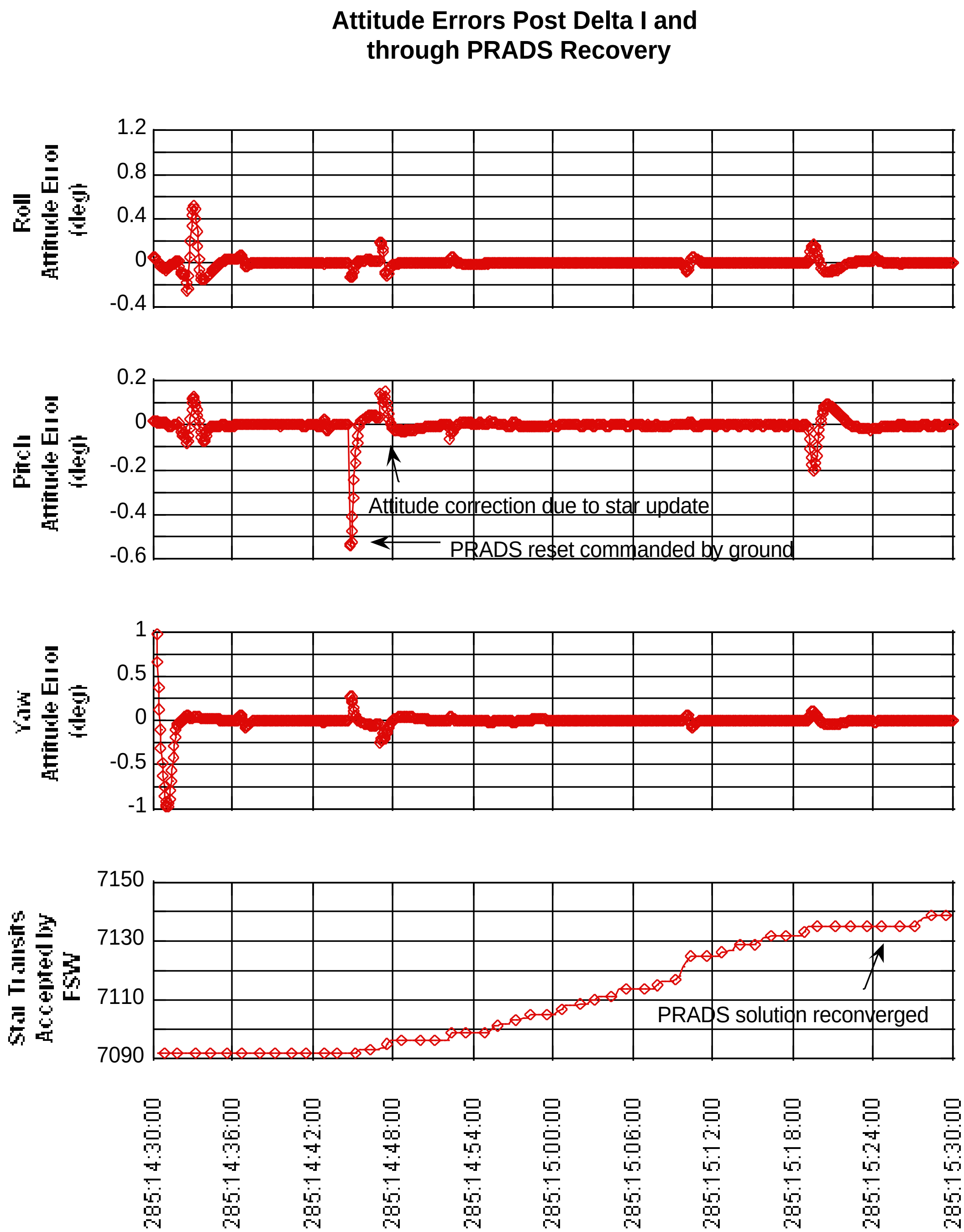


Figure 26 –Attitude Errors during PRADS Recovery

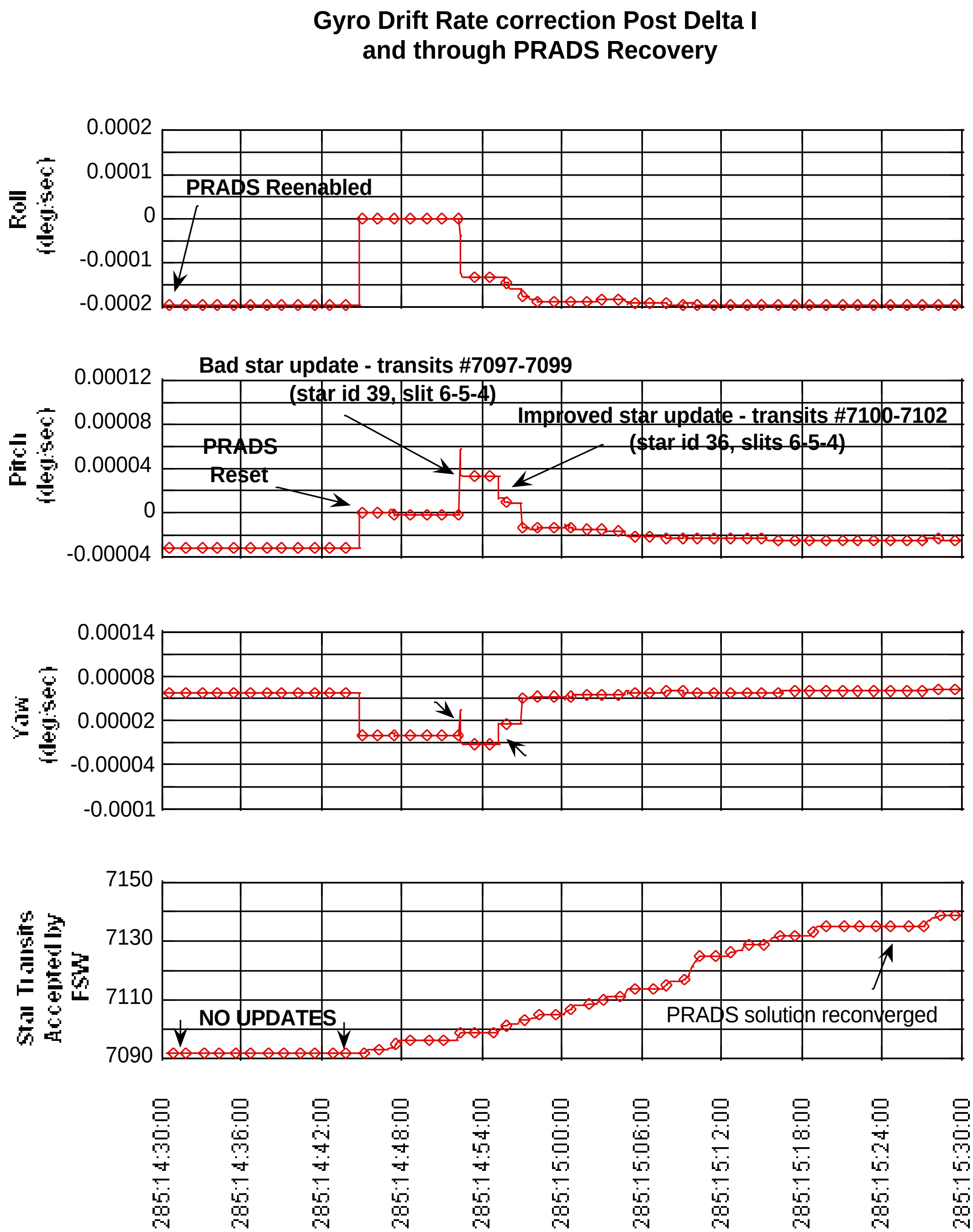


Figure 27 – Gyro Drift correction during PRADS Recovery

EPS Performance

Solar Array

The solar array is a 26-foot rotating array that tracks the sun. When the spacecraft is at the solar south pole, the array is in the 'index position' or at 0°. As the spacecraft moves through its orbit, the array rotates 360° in order to follow the sun. For all maneuvers using four jets for thrust, the solar array is parked at the 0° position to minimize torque on the structure and drive mechanism. The following sequence of events parked the solar array at the index position:

13:16:33z	solar array to open loop, slew fwd	(use 'slew' mode to rotate array)
13:23:45z	solar array to commanded position 0°	(send array to index position)
13:30:22z	solar array slows to 'fast' speed	(array slows as it approaches index)
13:31:20z	spacecraft enters 'day'	
13:31:23z	solar array at index position	

Sending the array to index placed the cell side of the array facing away from the sun at spacecraft sunrise. It was not until midway through the first yaw slew that the array began to face the sun and generate power. Because of the delay getting sun onto the array, the batteries continued to discharge and reached a maximum depth of discharge of 14% ±1%. After the first yaw slew was complete, the array was generating enough power to charge the batteries. Plots of solar array current and shunt current are included in **Figures 28** and **29**. The shunt plot shows there was some shunt current at the end of the first yaw slew and at the beginning of the second yaw slew.

After the return yaw slew, just after the estimated south solar pole crossing, the array was commanded back into its normal Ephemeris open loop control. This was done slightly after the estimated time to ensure the array did not have to slew in the reverse direction to reach the desired position (which was, at that point, slightly greater than 0°).

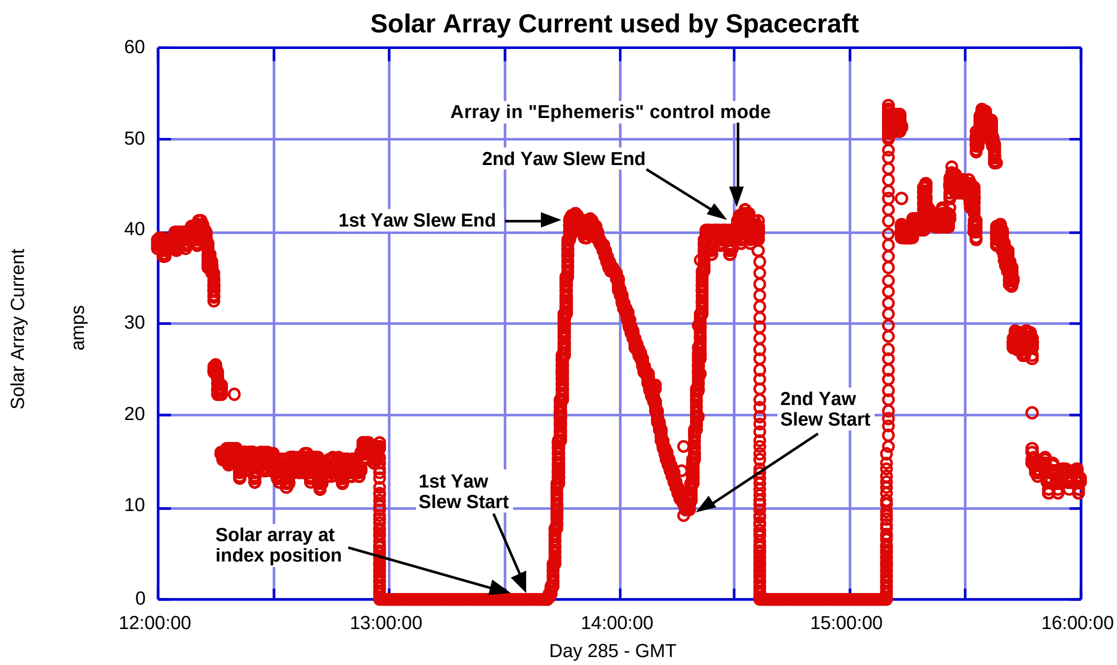


Figure 28 – Solar Array Current Used

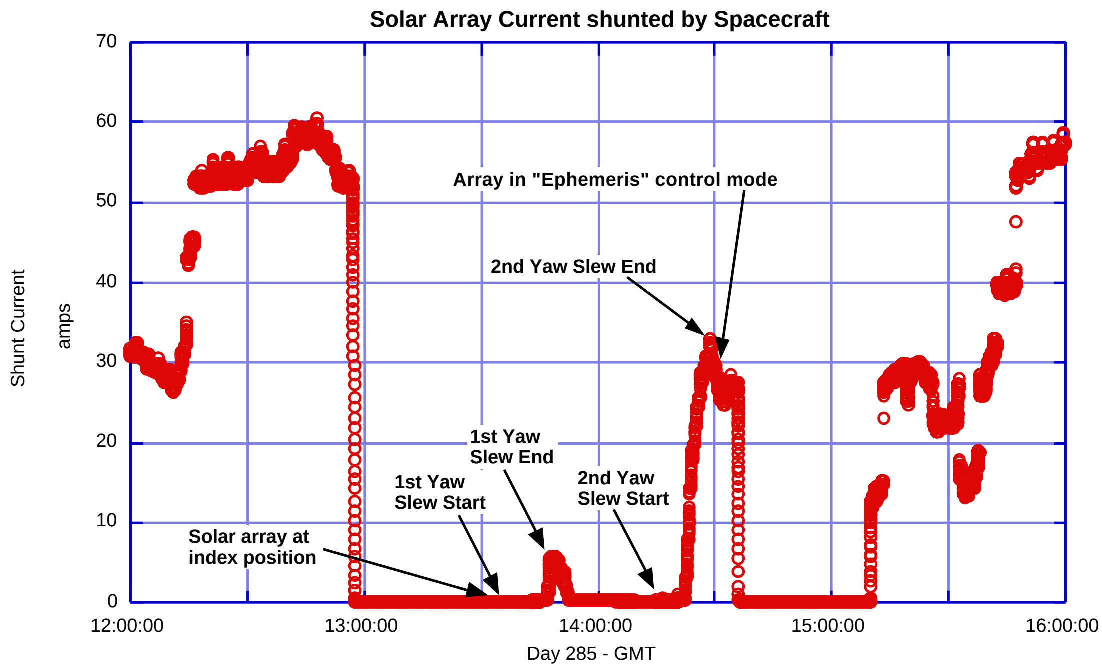


Figure 29 – Solar Array Current Shunted

A graph of solar array temperature is shown in **Figure 30**. Original concerns during the first Delta-i were about cooling the array too much and having large temperature transients altering the properties of the glue used to bond the solar cells to the substrate. Normal solar array wide range temperatures range from –74.6°C to +55.5°C. Temperatures during this Delta-i ranged from –74.6°C to 37.3°C. Due to the Delta-i being performed in daylight, there were no fluxuations on the low end of the array temperature. Because the array did not rotate and track the sun, it did not warm up as much as it normally does after eclipse exit. However, power output from the array is at a maximum right after eclipse exit, when the cells are cool. Array temperatures were back in their normal range on the next orbit.

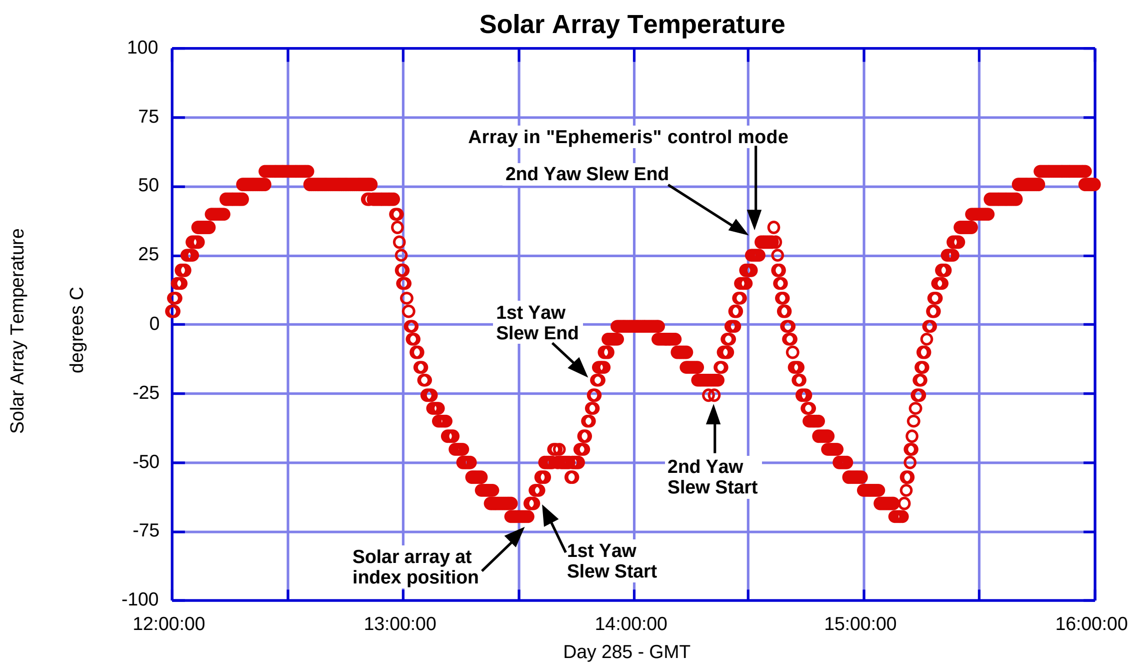


Figure 30 – Solar Array Temperature

Batteries

Soon after the sun was present on the array, battery charging began and continued (although not always at the maximum rate of 13 amps) until the S/C entered Earth shadow (after the burn and both yaw slews were complete). Approximately three to five minutes after the end of the first slew, the orbit geometry began decreasing array exposure to the Sun. The return yaw slew brought the array back into full sunlight and the batteries began charging at full rate again. The batteries were both very close (within a few percent) to full state of charge after the return slew when the spacecraft entered the normal Earth shadow. However, because they were not at their specified full capacity, FSW had commanded both Battery Charge Regulators (BCRs) to use Voltage/Temperature (V/T) curve 4 on the next charging cycle. (V/T 5 is the normal curve used for charging.) The batteries met 100% State-of-Charge (SOC) on the next orbit and FSW commanded the BCRs to use V/T 5 again.

Graphs of battery charge current, discharge current, and depth of discharge are included in **Figures 31** through **36**. The battery charge plot follows the solar array current plot in that the batteries were charged when the array was producing current. The batteries were able to charge part of the time at the rate of 13A.

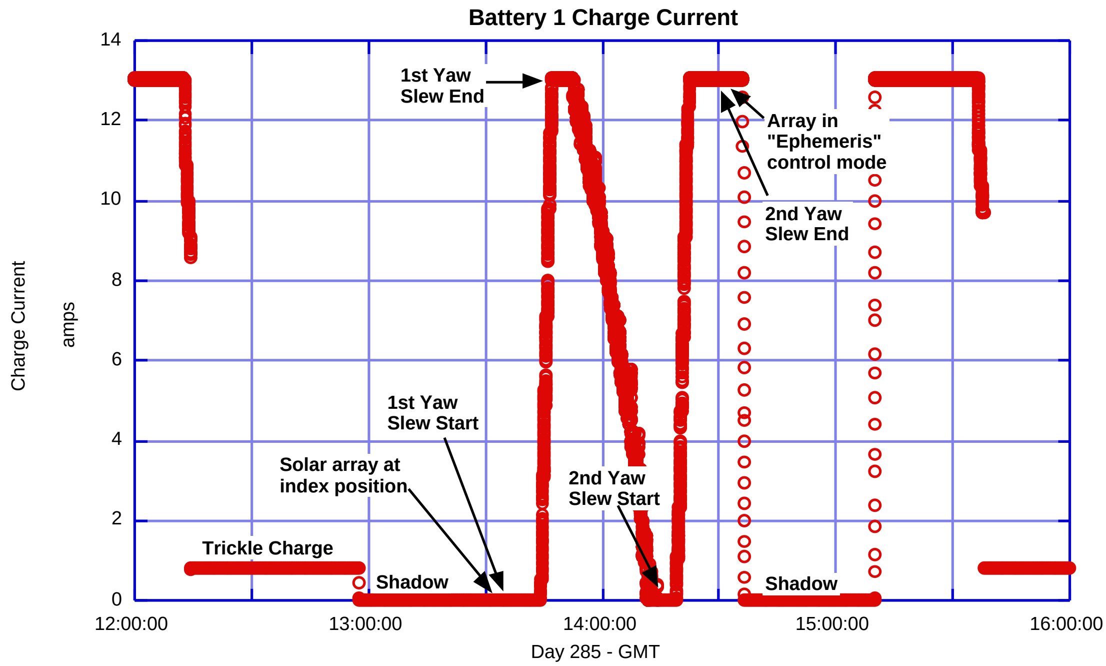


Figure 31 – Battery 1 Charge Current

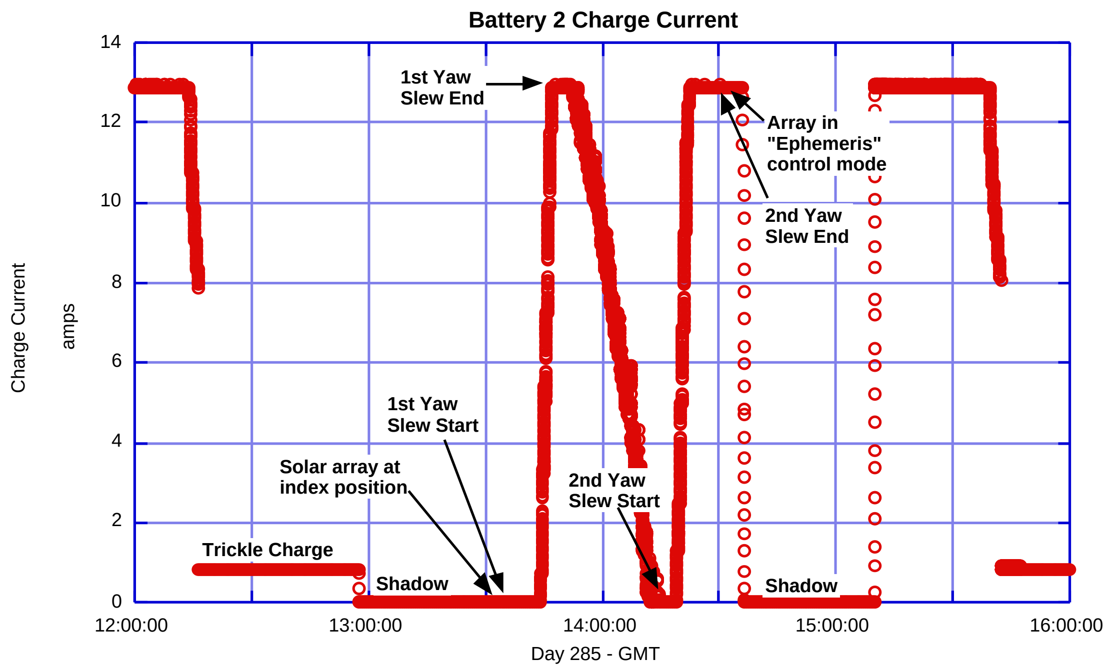


Figure 32 – Battery 2 Charge Current

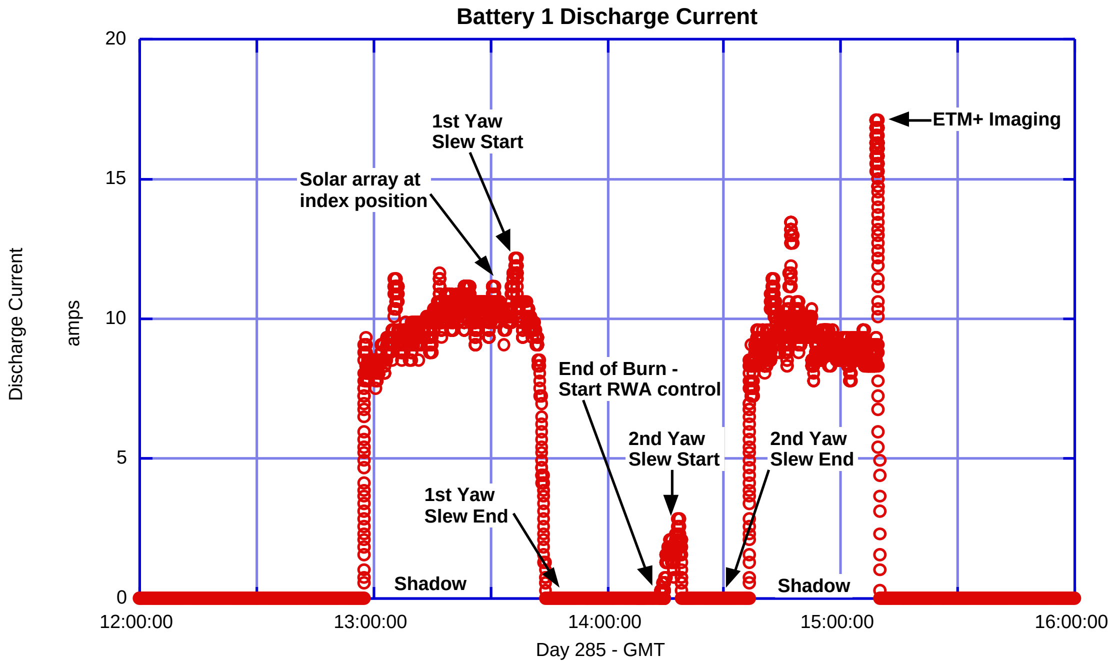


Figure 33 – Battery 1 Discharge Current

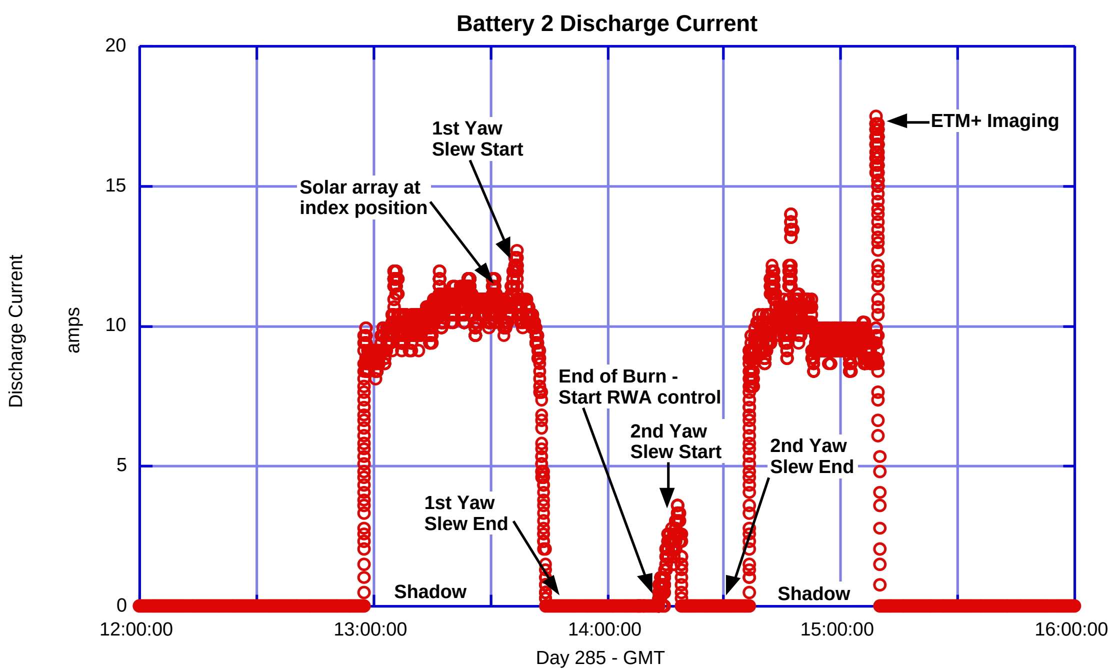


Figure 34 – Battery 2 Discharge Current

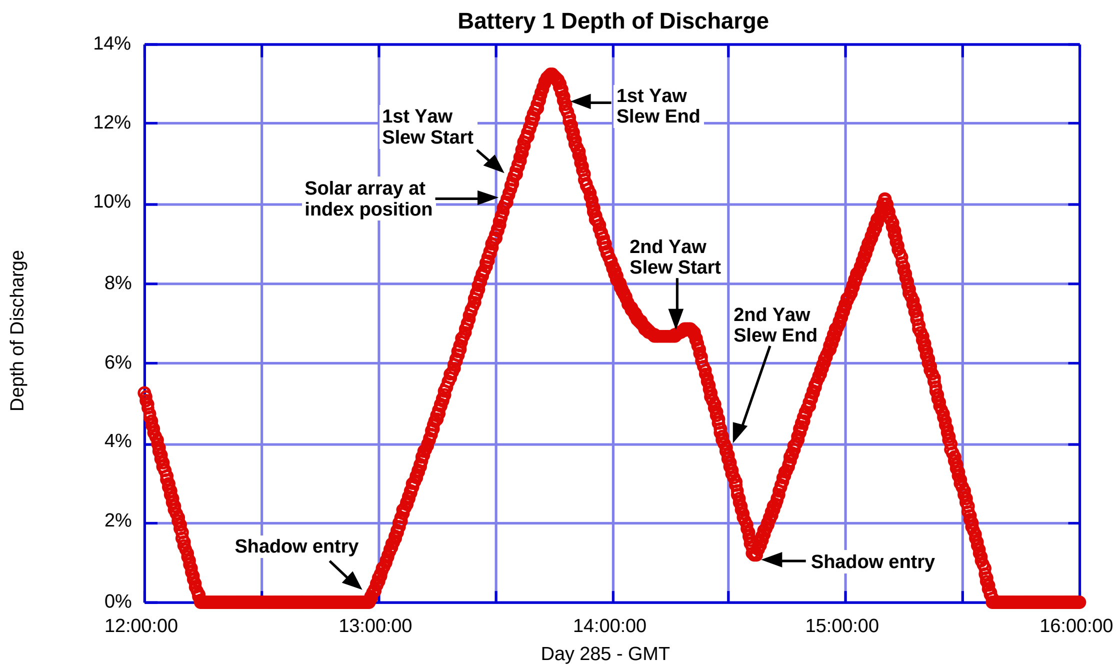


Figure 35 – Battery 1 Depth of Discharge

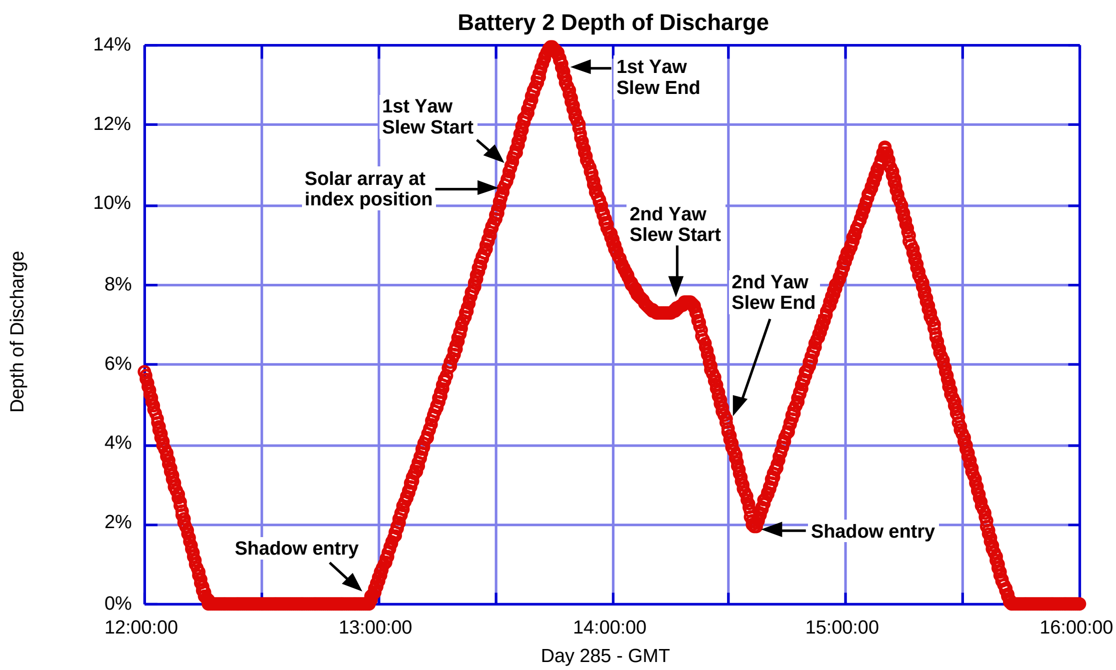


Figure 36 – Battery 2 Depth of Discharge

Battery Pressure

Battery pressure is an indicator of the state of charge of the battery. As battery state of charge increases or decreases, so does the pressure. Battery pressure is included in this report due to the recent concern about the pressure and because the batteries had a slightly deeper discharge during the Delta-i. Depth of discharge was about 13% on battery 1 and 14% on battery 2. Normal orbital depth of discharge is about 9% on battery 1 and 2. The slightly higher discharge on the batteries appears to have no long-term effect on the pressure of either battery. While the EOCP and EODP (end of charge pressure and end of discharge pressure) followed the state of charge of the batteries for that orbit, pressures were back to there ‘normal’ readings on the next orbit. The included pressure plots in **Figures 37** and **38** only show pressure from 12:00:00Z to 16:00:00Z on the day of the Delta-i.

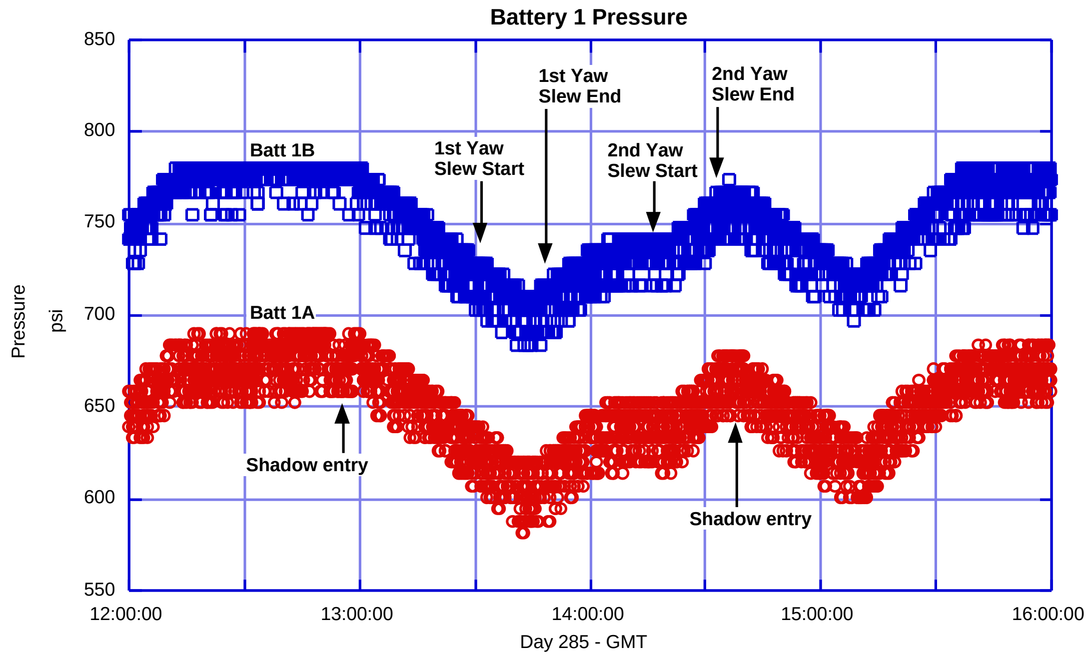


Figure 37 – Battery 1 Pressure

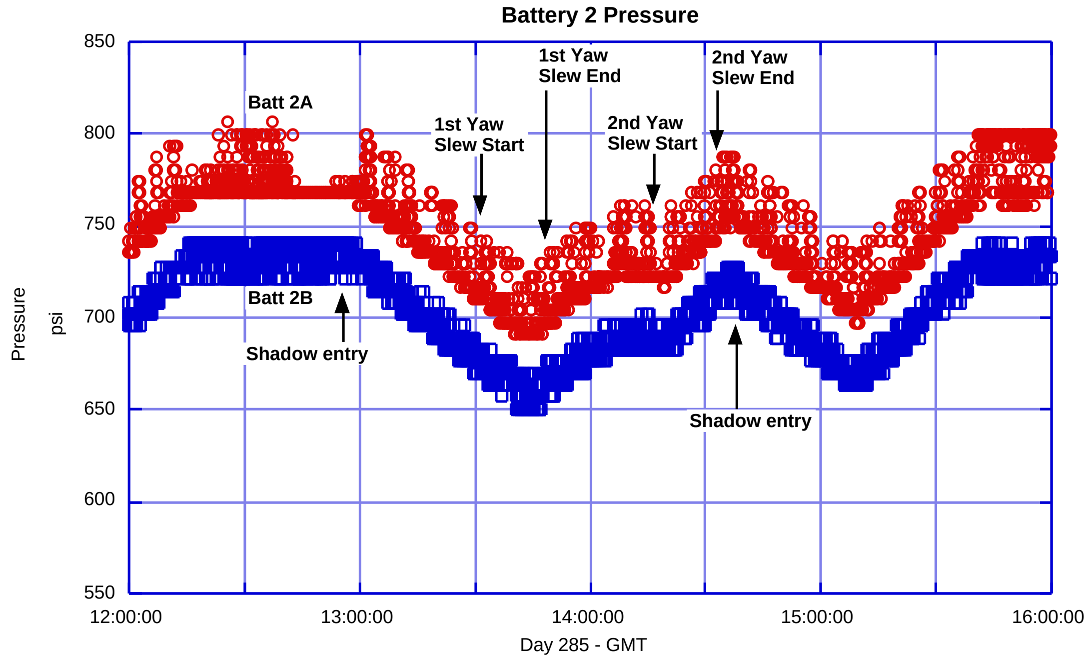


Figure 38 – Battery 2 Pressure

ETM+ Performance

Imaging operations were suspended for 30.5 hours for the Delta-i operation. The ETM+ cooler door was moved to the outgas position about 1/2 orbit before the start of the burn; this was done to minimize the warming affect in the CFPA (Cold Focal Plane Assembly). There was a special request from the Landsat Project Science Office (LPSO) requesting imaging during ETM+ cool down and to cool down the CFPA to 87K instead of 89K. Imaging was performed during the cool down to capture radiometric readings of the detectors at different temperature ranges. The ETM+ cooler door was moved to the outgas position to reduce the possibility of sun exposure if an anomaly from the Delta-i maneuver were to occur and to reduce the possibility of contamination during the operation. In addition, while the spacecraft is yawed out by 90.75° and passing near the south polar region, the Sun would impinge on the cooler if the door were to be left in the Open position. As expected, shortly after the cooler door was placed in the Outgas position (within 7 minutes) the CFPA rose into its "Red" operating temperature limits (>109K).

Below is a timeline of ETM+ and selected other events during the Delta-i sequence.

285-13:05:54.5	ETM+ cooler door at OUTGAS
	ETM+ in INIT mode
	ETM+ blackbody htr control on / T1 select
	ETM+ blackbody T3 select
	ETM+ baffle htr control on
	ETM+ cfpa htr control on / T1 select / tlm on
285-13:35:38.2	Slew 90.75 degrees
285-13:52:44.3	Burn Starts
285-14:12:16.9	Burn Ends
285-14:17:40.0	Slew -90.75 degrees
285-14:42:52.0	ETM+ cooler door in Open position
	ETM+ in INIT mode
	ETM+ cooler door "open" direction selected
	ETM+ cooler door move enabled
	ETM+ cooler door move disable
	ETM+ blackbody htr control off
	ETM+ baffle htr control off
	ETM+ cfpa htr control disable
285-14:48:26.6	ETM+ in STBY mode (ready for periodic imaging during CFPA cooldown)
285-14:49:08.0	ETM+ CFPA htr DISABLED
285-14:49:26.3	ETM+ Blackbody htr DISABLED
285-14:49:48.9	ETM+ Baffle htr DISABLED
285-15:00:00.0	From this point until approximately 286-22:00:00, the ETM+ was cycled 12 times.

286-01:24:02.5 ETM+ Blackbody htr ENABLED
286-01:24:37.9 ETM+ Blackbody T3 selected

286-09:42:19.7 ETM+ Baffle htr ENABLED

286-17:47:29.1 ETM+ CFPA htr ENABLED

Cooler Door

As soon as the cooler door was commanded to outgas position, it began to cool. The cooler door was no longer pointing downward to earth, but instead to deep space, with its temperature oscillating between -62.7° C. and –56.7° C (normally, the temperature fluctuates over an orbit from approximately 0° to -46°). After the Delta-i maneuver and slew back to normal orientation, the cooler door was commanded back to the open position and returned to its normal temperature profile. The temperature profile from this year Delta-i is similar to last year's and is shown in **Figure 39**.

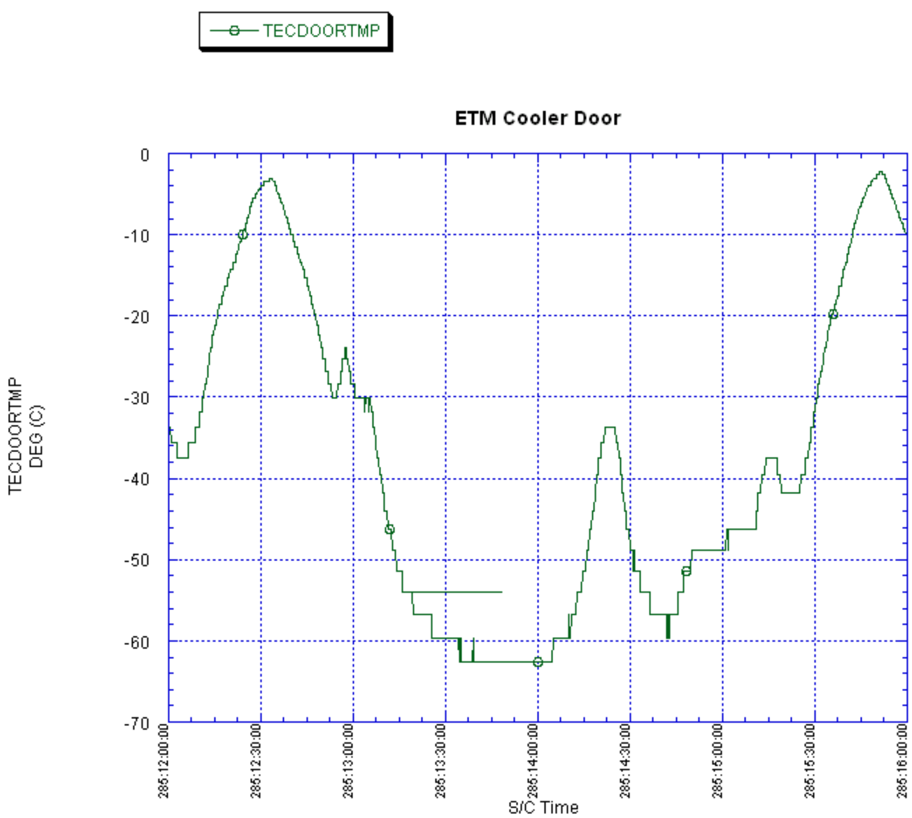


Figure 39 – ETM+ Cooler Door Temperature

Cold Stage A&B (Cold & Hot) and CFPA

As soon as the cooler door was moved to outgas position, Cold Stage A&B and CFPA temperatures began to rise as expected. Delta-i set-up was altered this year in an attempt to minimize the amount of time the cooler door remained in the Outgas position (shortening cooldown time). This year the cooler door was in outgas position for about an orbit, allowing the CFPA to warm up to 160K. This is about 30K cooler than last year's temperature.

The Cold Stage A (Cold) temperature readings are valid below 125K, any temperature above 125K is beyond the sensor's limit. Cold Stage B (Hot) temperature is used for readings above 125K, but are not as accurate as the Cold Stage A below 125 K. The optimum operating temperature for the CFPA is 91K.

Normally cool down of the CFPA to 89K is done to comply with SBRS and NASA recommendation, but at LPSO request (and SBRS concurrence) the CFPA was cooled down to 87K before enabling its heater. It took approximately 2 full orbits to cool the CFPA the extra 2K, making total cool down time this year about the same amount of time of last year's Delta-i. Upon reaching 87K, the CFPA heater was enabled by the FOT. It took more than 3 hours for the CFPA to rise to its operating temperature of 91K. During the 1999 Delta-i the CFPA heater warmed up to 91K from 89K within minutes.

CFPA heater current started to increase during the cool down (when its temeperature was at 108K) even though the heater was disabled. As the CFPA got cooler, its heater current kept increasing. It is assumed that when the CFPA heater is disabled, that it will not draw current. CFPA temperature readings become noisy when the heater current begins to rise, also Cold Stage B temperature gets noisy as it cools. The increase in CFPA heater current is due to a shared a common return with Cold Stage A & B and CFPA Control and Monitor temperatures. The current reading is invalid under these conditions. **Figure 40** shows plots of CFPA and Cold Stage temperatures.

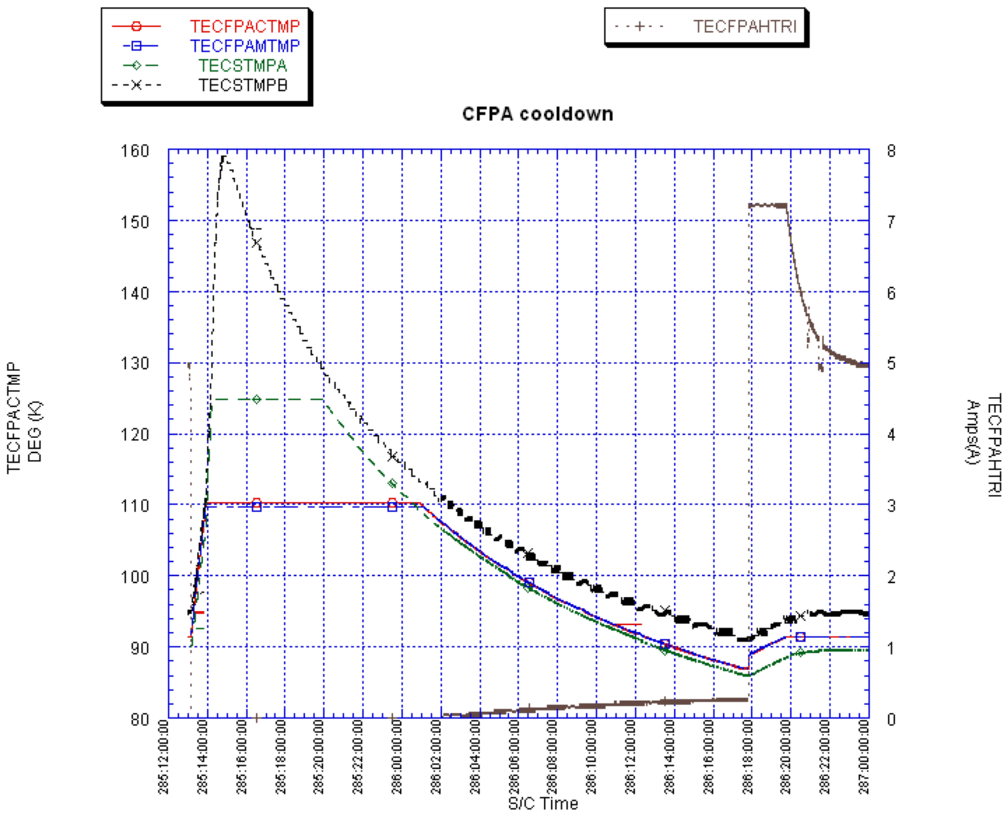


Figure 40 – CFPA and Cold Stage Temperatures, and CFPA Heater Current

Figure 41 shows a comparison between 1999 and 2000 CFPA and Cold Stage temperatures. Cooldown signature is identical for both years. This will make it easier to predict cooldown time in the future.

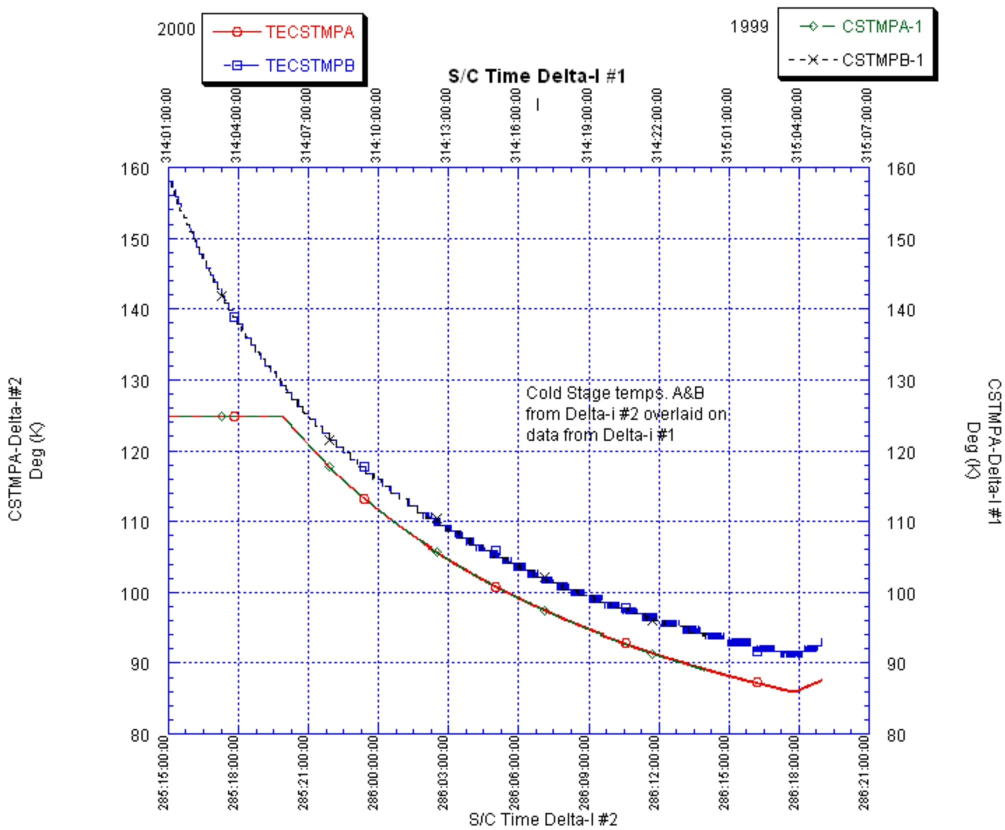


Figure 41 – Cold Stage Temperature Comparison (1999 to 2000)

During the 1999 Delta-i, the baffle heater was not enabled for most of the cool down. During the 2000 Delta-i, the baffle heater was enabled for the last 8 hours of the cool down. Despite this fact, the Cold Stage cooling rate was identical for both Delta-i's (see **Figure 41**).

Power Supply

The ETM+ Power Supplies are located in the Main Equipment Module (MEM) and were not used during the Delta-i but were used during setup and cool down. The power supplies were used to place the ETM+ in the INIT and Standby mode, to move the cooler door from open to outgas position, and for imaging during cool down.

During cool down, the MEM heat sink temperature started to decrease immediately. Imaging during cool down helps keep the AEM (Auxiliary Equipment Module) and MEM heat sinks in ideal operating temperature range. The MEM heat sink did drop to 11.2° C although the MEM standby heater is supposed to close at 12.8° C. During the 1999 Delta-i cool down, the MEM Heatsink did not go below 12.8° C. It is not known why the MEM heat sink dropped below 12.8° C before imaging started during cool down. During cool down, the ETM+ Power Supply Heat sink never dropped below 12.8° C as seen in the figure below.

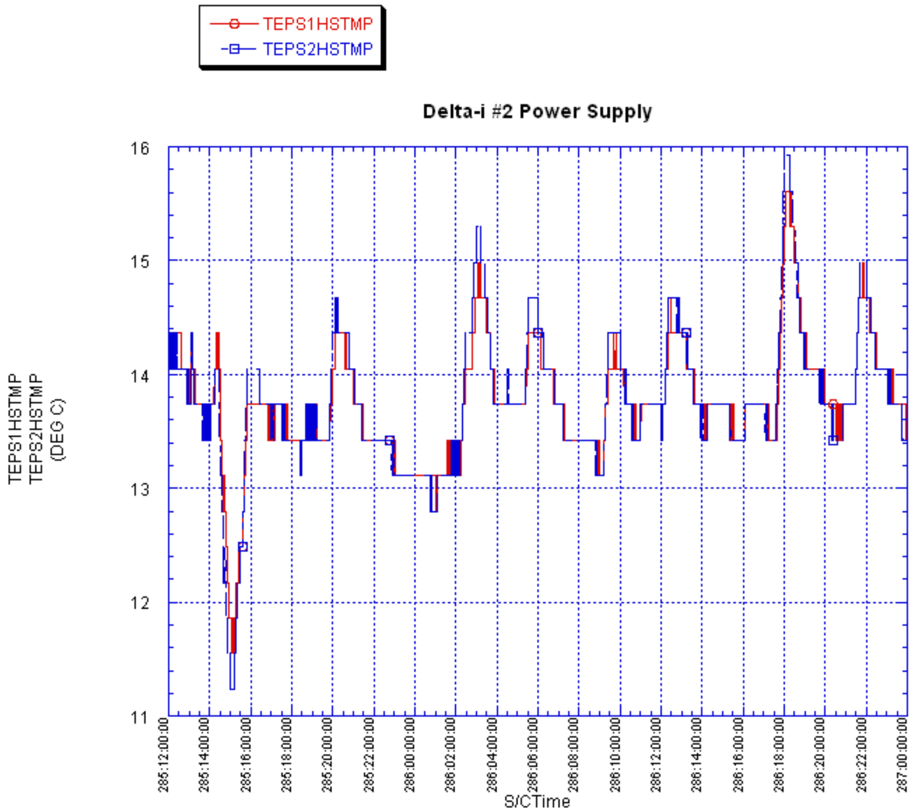


Figure 42 – Power Supply Temperature

Blackbody and Baffle

During the Delta-i maneuver the Blackbody and Baffle heaters were left on and stayed at the desired operating temperature. After the Delta-i maneuver, the cooler door was moved back to the open position, outgas heaters were kept off, and "normal" was chosen as the ETM+ heater configuration (baffle, blackbody, and CFPA heaters enabled). A separate Engineering Request (ER) was performed to turn off the baffle, blackbody and CFPA heaters during cooldown. When the CFPA temperature reached 110K and 95K, the blackbody and baffle heaters respectively were turned on. These points were chosen in advance by the LPSO. **Figures 43** and **44** shows the baffle temperature during the cooldown.

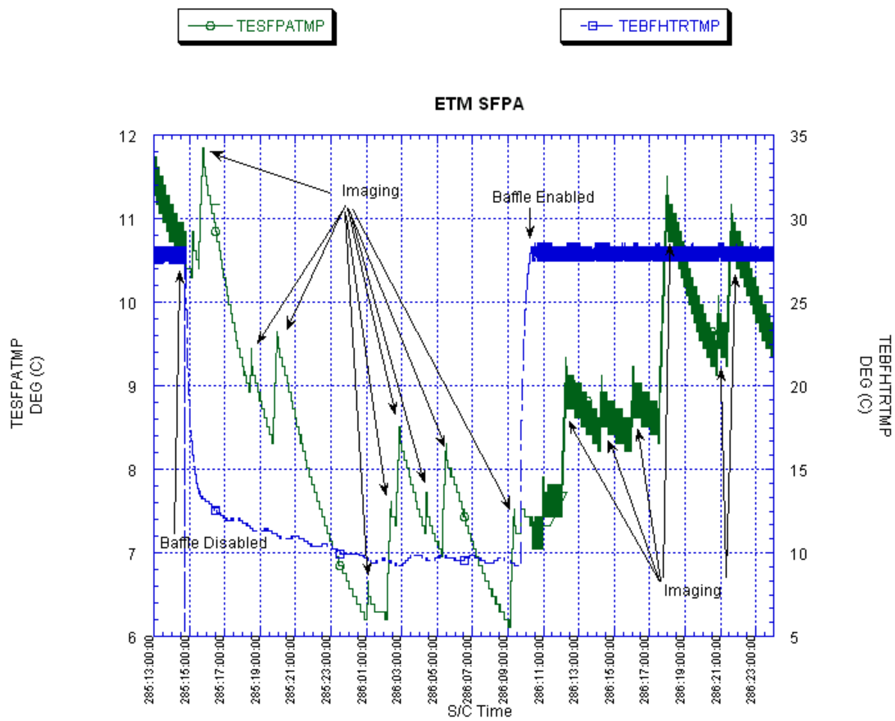


Figure 43 – Si Focal Plane and Baffle Temperatures

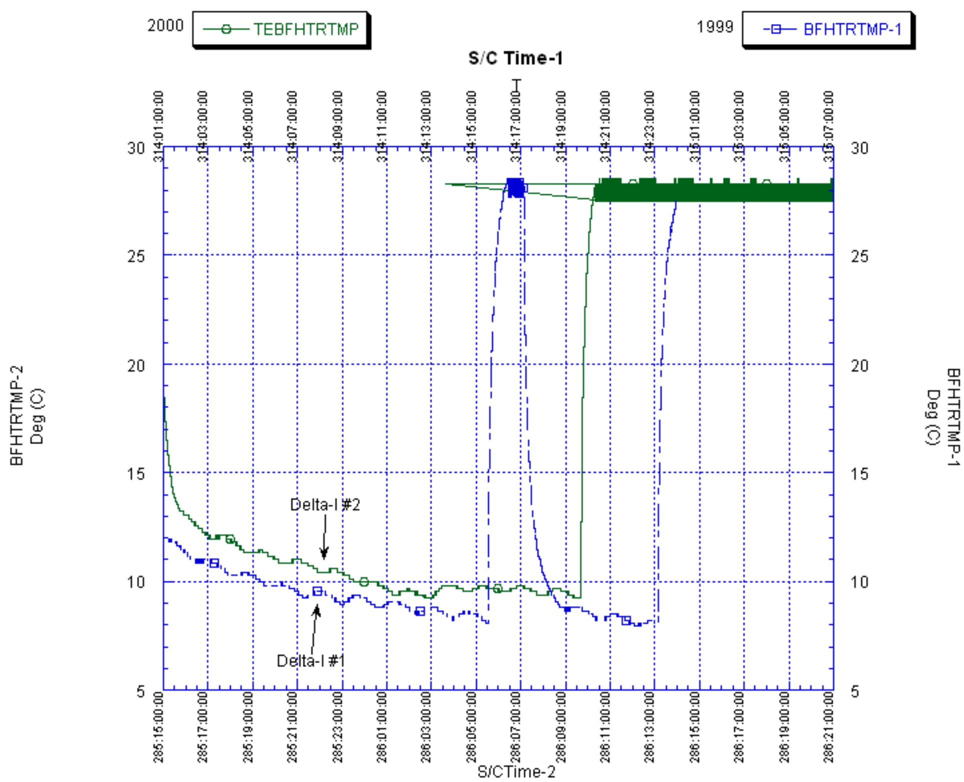


Figure 44 – Baffle Temperature Comparison (1999 and 2000)

Temperature profiles from 1999 and 2000 Delta-i show that cool down rates were very similar with different initial temperatures. In the 2000 Delta-i coldown, the baffle heater was on longer than during the 1999 sequence. This did not seem to change the cool down of the CFPA. In the 2000 Delta-i cool down, the Blackbody heater was turned on at 01:24 GMT and changed the cool down profile of the Baffle. Enabling the Blackbody heater during cool down also did not change the cool down profile of the CFPA. Almost no evidence of thermal leak into the CFPA from the ETM+ Baffle and Blackbody heaters was evident.

Scan Line Corrector (SLC), Telescope Housing, Primary and Secondary Mirror
The central baffle, primary and secondary mirrors are located inside the telescope housing. The SLC, calibration and backup shutter are next to the telescope which all are located in the center of the ETM+. The baffle heater is also located within the telescope housing and helps keep the mechanisms warm. With the baffle heater off, the telescope housing, baffle support tube, scan line corrector (SLC), primary and secondary mirrors cooled down. During cool down the imaging runs kept the mechanisms slightly warmer, preventing possible damage to all mechanisms. When the ETM+ is not imaging, the mechanisms are not in use and will cool down. During cooldown the mechanisms temperatures had to be monitored because if they get too cold for an extended amount of time, damage may occur. Even though imaging was performed during cool down, the mechanisms cooled lower than during normal operations because the baffle heater was disabled and imaging frequency was lower than normal. As soon as the baffle heater was enabled the SLC average temperature increased as shown in **Figure 45**. **Figure 46** shows Telescope housing and Baffle temperatures.

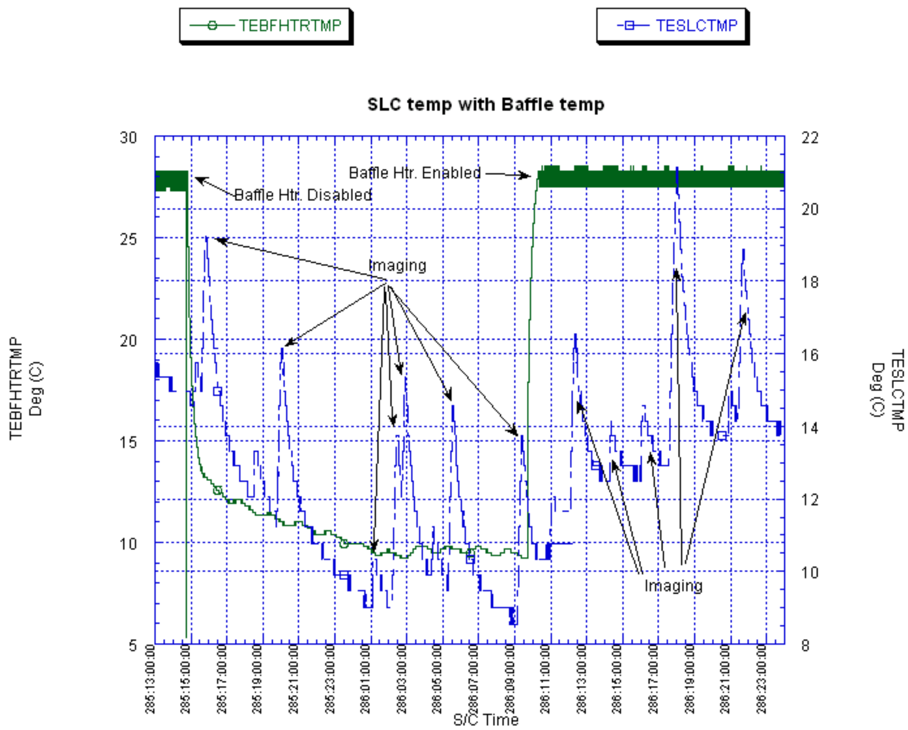


Figure 45 – Scan Line Corrector and Baffle Temperature

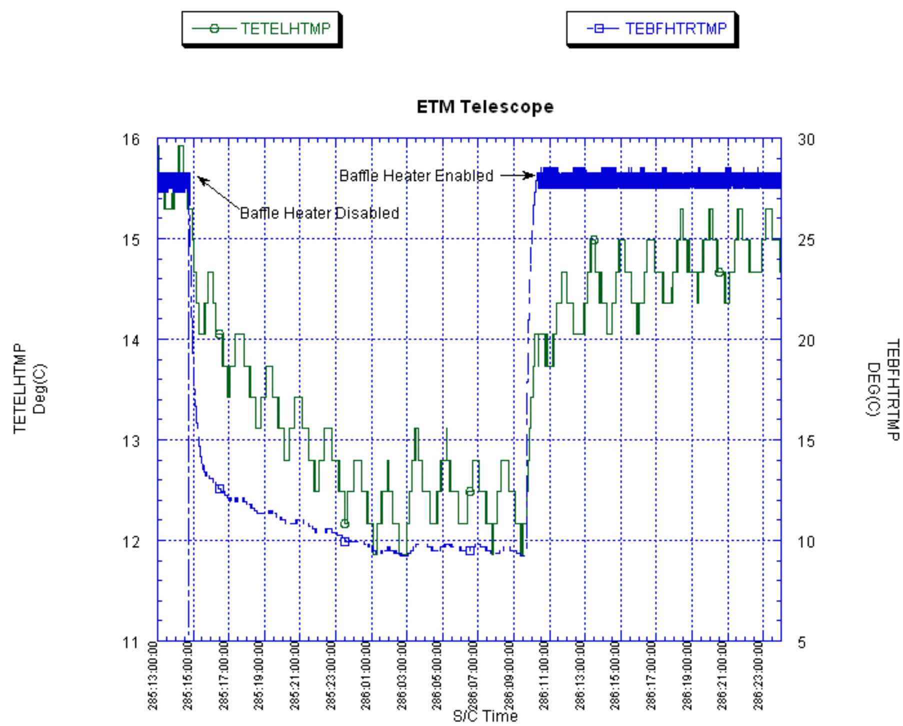


Figure 46 – Telescope Housing and Baffle Temperatures

<u>SMA</u>

Throughout the maneuver, the SMA Standby and Safestate heaters were left enabled to keep the SMA at a safe temperature. The scan mirror operation is temperature dependent; it works efficiently when the SMA is at 24° C. Throughout the Delta-i maneuver and cool down the SMA standby heaters kept the SMA at an average temperature of 21°C - 22°C, which is about 1°C - 2°C below its normal operating temperature. If the SMA standby heaters cannot keep the SMA above 20° C, the SMA safestate heaters close to keep the SMA from cooling down. The SMA safestate heater closes at 20° C for the SMA +Z with an output of 1.78 amps and opens at 25° C. The only action that was needed for the SMA was to monitor and make sure the SMA stayed in the vicinity of 21° C.

Figures 47-50 show the temperature profile of SMA ±X, SMA ±Z, SMA Torque and SMA electronics. With imaging during cool down, there was no concern about the SMA housing getting too cool because imaging helps warm up the SMA housing. None of the SMA sensors went below 20° C except for the SMA electronics, therefore the SMA Safestate heater thermostat did not close.

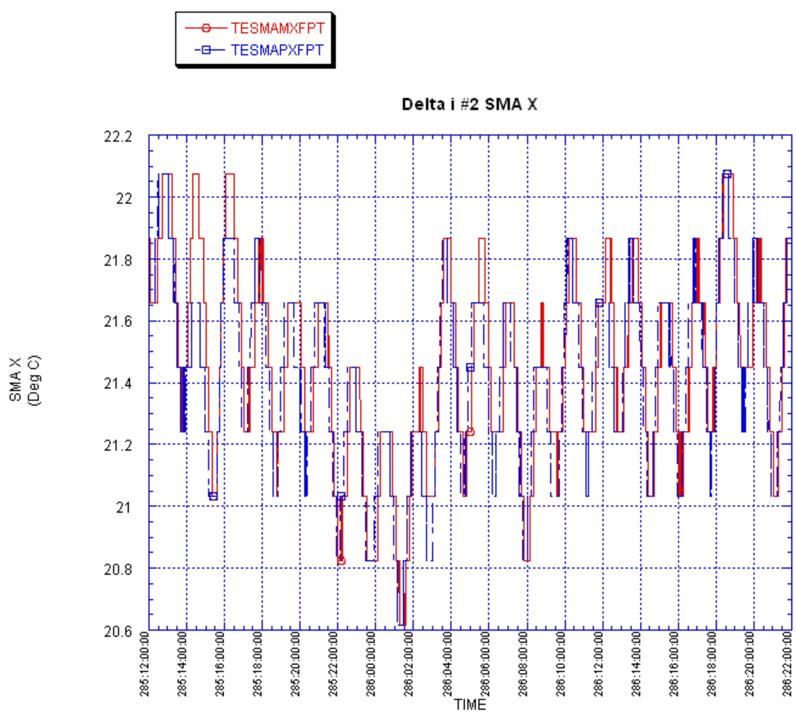


Figure 47 – Scan Mirror Assembly Temperature

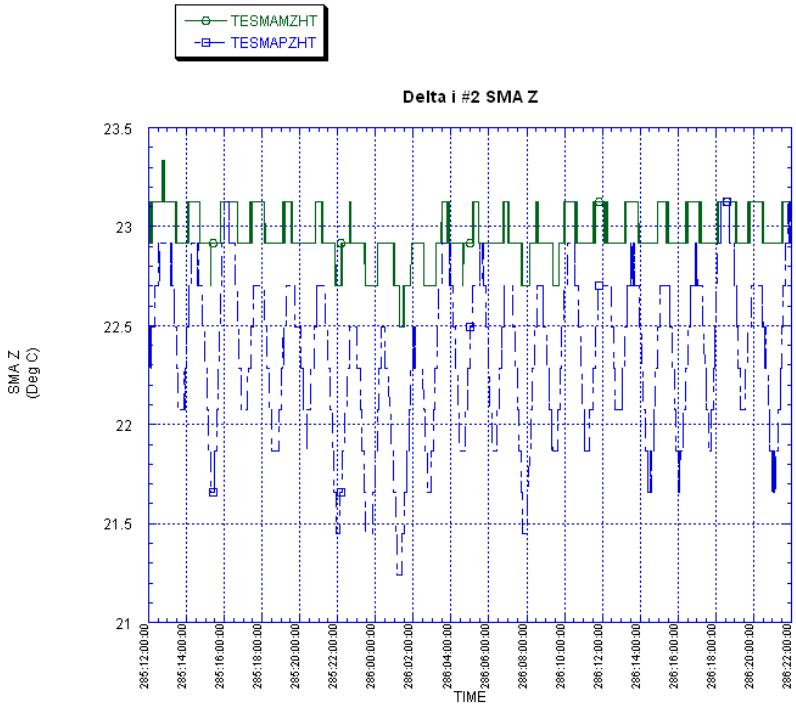


Figure 48 – Scan Mirror assembly + and – Z Temperatures

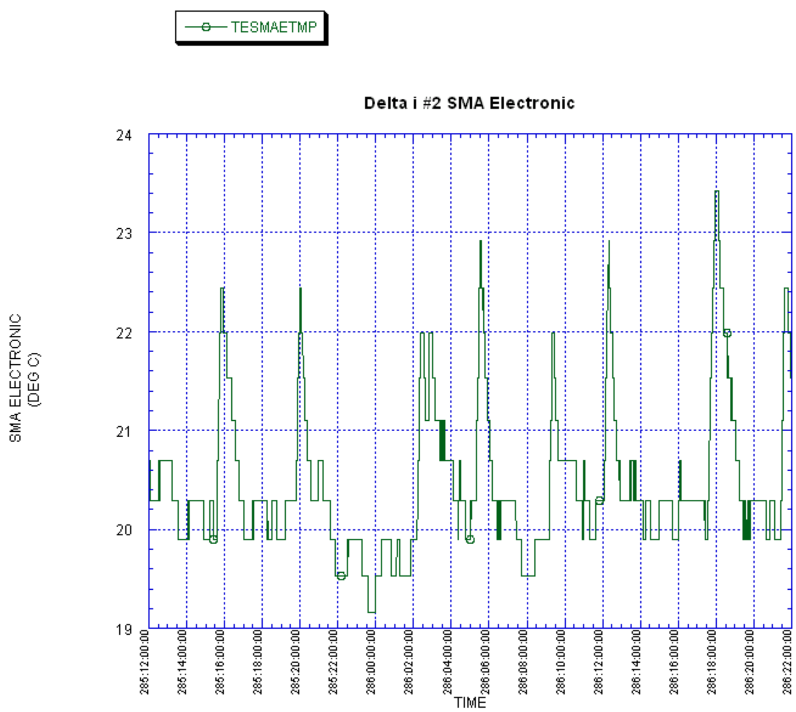


Figure 49 – Scan Mirror Assembly Electronics Temperature

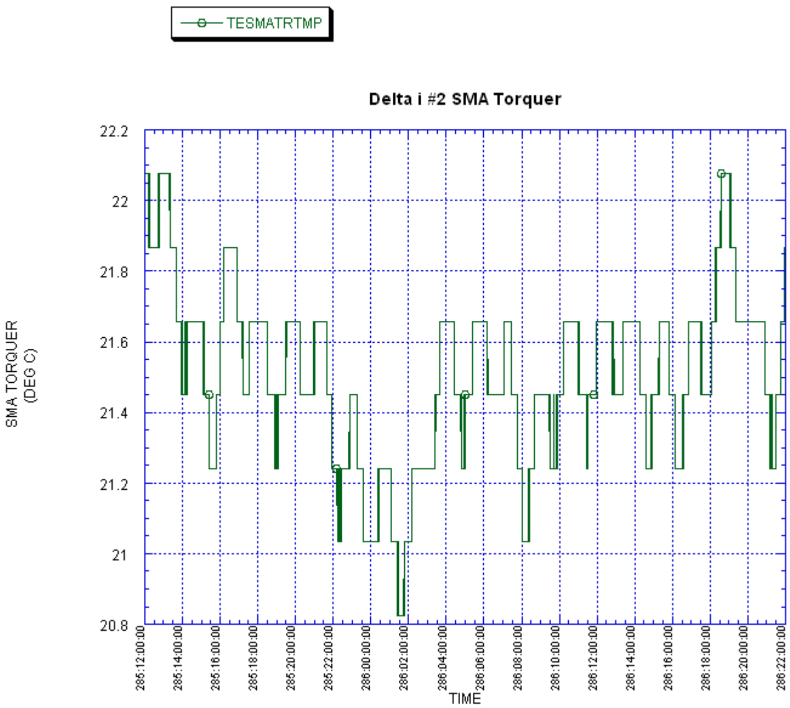


Figure 50 – Scan Mirror Assembly Torquer Temperature

Conclusions/Recommendations

While all systems performed as expected during the Delta-i sequences, there were a few recommendations the FOT would like to make for future maneuvers of this type.

ACS/RCS

As shown in **Figure 2** - Skew Wheel Spin down to 0 RPM prior to “Slew-Burn-Slew” and **Figure 13** - Wheel speed and torque commands issued during Yaw Slew, the Pitch and Yaw wheels reached a quiescent steady state (close to 0 RPM) approximately 1 hour prior to the start of the first slew. To minimize the amount of time that the reaction wheels are at or close to 0 RPM, it is suggested that the time to initiate the skew spin down move closer to the first slew event. As the spin down takes a lengthy TDRSS contact (20 minutes plus), it is recommended that spin down occur partially in the blind and be executed from the Preburnd RTCS.

In general, all FSW compressed floating-point telemetry parameters need to be reviewed for proper scaling. As an example, the Rate error data in **Figure 5** seems “noisy” due to clamping of very small numbers to 0. In certain instances, the need for precise data is necessary (statistical measures, etc.) and the current scale settings do not allow this.

In order to include TEMPBIAS into PCD, FSW must convert this data from a floating-point number to a fixed-point number. During this conversion process, the possibility exists that a mathematical Fixed-Point overflow error could be generated within the SCP. If this occurs a SCP switch is requested. In order to minimize the risk of this occurring, the scale value used during this Delta-i should be reinstated during future maneuvers. An alternative (and more generic) fix to this serious problem would be to have the FSW logic changed so that a mathematical error of this type does not halt SCP processing.

Prior to the 2000 Delta-i an attempt was made to calibrate the gyros by performing and analyzing gyro offset data. After several weeks of analysis and discussion, a consensus on the proper uplink values was NOT agreed upon and the gyros remained at their pre-launch cal values. In the future, if the star predictions become harder to qualify or if the gyros start to drift abnormally, the gyro alignment effort must be completed. This could make reacquiring Precision control difficult during a Delta-i or some other type of anomaly. Likewise, the star catalog needs to be updated for the same reasons.

It is good practice to command FINE limits when the spacecraft attitude/rates are near steady state; avoid skew wheel reactivation and thermal snap events.

The time of year a Delta-i is scheduled for influences the star field environment that will be available for reconvergence of the PRADS solution. Star prediction runs should be relied upon to predict the best available time frame to schedule future Delta-i's, as this would ease the process of star identification and convergence upon completion of the Delta-i. Experience with LSIM and review of historical star data demonstrates that some days are better for star identification than others.

Evaluating the results from the 1999 and 2000 Delta-i burns, the FOT would like to open a discussion on reducing the magnitude of the yaw slews. A smaller yaw angle (say 90.5° instead of 90.75°) would yield a smaller WRS drift rate after the burn while still reliably producing an Eastward drift.

Between Delta-i burns, it is recommended that jets 1-4 are used more uniformly in the executuion of Delta-V burns. Previously, only jets 1&3 were used until a few weeks prior to the the Delta-i when 2&4 were used to gather last minute performance data. In order to predict the efficiency and final results of the Delta-i burns the current performance of jets 1-4 must be known as well as any long term trends. Interspercing the use of both of Delta-V jet sets (1&3 and 2&4) in those time periods between Delta-i burns will provide this data.

ETM+

After the slew-burn-slew when the cooler door is opened, the cool down heater configuration should be CFPA heater off, and Baffle and Blackbody heaters on. There is not much evidence showing any thermal leak from the baffle and blackbody heaters to slow the cooling process of the CFPA. The second Delta-i cool down had the Blackbody and Baffle heater on much longer than the first cool down. Keeping the baffle heater on will at least keep the mechanisms inside the ETM+ from cooling excessively. If the cool down rate appears to be proceeding slower than that experienced in this cool down, the baffle and blackbody heaters may be turned off to quicken the cooling process.

In future Delta-i plans, it may be requested that imaging take place during the cool down. The necessity of this imaging should be weighed against added operational complexity. Clear guidelines for ETM+ configuration and thermal limits must be laid out prior to the operation. Possible changes to the scheduling software may be needed to routinely process special imaging/downlink sequences like the one executed during this cooldown.

Appendix - A - Detailed Timeline of Events

**************	**
285-12:10:00.0	TDS 7935
285-12:11:50.7	Procedure PREDELI started.
285-12:12:04.9	Skew wheel = DISABLED
285-12:12:27.4	Maneuver Torque filter = USE state
285-12:14:07.4	TEMPBIAS scale changed to x’0020’
285-12:16:32.6	Abort limits changed to +/- 5° on SCP 1
285-12:18:40.4	Abort limits changed to +/- 5° on SCP 2
**************	**
285-12:43:55.0	MGS 7935
285-12:52:42.2	Prime/Redundant Catbeds ON
285-12:52:43.1	RTCS 22 ACTIVE state
**************	**
285-13:02:00.0	TDZ 7935
285-13:03:24.6	Procedure ETMCDOG started.
285-13:05:54.5	ETM+ cooler door at OUTGAS
285-13:07:17.3	Procedure RTCSCONFIG started.
285-13:07:30.9	SFRTCS 20 = VALID
285-13:16:33.8	Solar Array to Open Loop, Slew Fwd
285-13:23:45.8	Solar Array to Cmd Position, 0 deg
**************	**
XXXXXXXXX	XXXXXXXXXXXXXXXXXXX OUT OF VIEW
285-13:30:22.0	Solar Array slows to FAST
285-13:31:21.0	Solar Array at Index position
**************	**
285-13:31:37.0	SGS 7936
285-13:34:30.8	RTCS 20 ACTIVE
285-13:34:32.0	SFFSYSMOM_0 entered SYSTEM state; (new value = 1; old value = 0).
285-13:34:37.0	SFCRSATTLIM entered COARSE state; (new value = 1; old value = 0).
285-13:34:44.4	SFSTLOAD entered YES state; (new value = 1; old value = 0).
285-13:35:03.2	SFPTSHER entered YES state; (new value = 1; old value = 0).
285-13:35:04.3	SFSYNCHDTABID entered DATAB_1 state; (new value =1; old value =0).
285-13:35:38.2	SFSMODE entered SLEW state; (new value = 1; old value = 4).
**************	**
285-13:45:00.0	TDS 7936
285-13:49:49.9	Procedure RTCSCONFIG started.
285-13:50:03.9	SFRTCS 21 = VALID
285-13:52:44.3	Burn Starts; RTCS 21 = ACTIVE
285-14:12:16.9	Burn Ends; ACS mode = Precision
**************	**

Appendix - A - Detailed Timeline of Events

XXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXX OUT OF VIEW

285-14:17:40.0	Yaw slew starts
**************	**
285-14:21:52.0	MGS 7936
285-14:29:30.0	Yaw slew ends
285-14:29:59.5	Procedure DATAB started.
285-14:30:04.6	Entered DATAB_2 state
285-14:30:39.3	Procedure GOTOPREC started.
285-14:30:50.3	SFSMODE entered PRECISION state; (new value =4; old value =1).
285-14:31:11.2	Enable Star processing
285-14:31:50.9	Solar array in Ephemeris mode
**************	**
285-14:38:00.0	TDZ 7936
285-14:40:33.0	Procedure ETMCDOG started.
285-14:42:52.0	ETM+ cooler door in Open position
285-14:44:46.0	Full Reset of PRADS filter
285-14:48:26.6	ETM+ in STBY mode
285-14:49:08.0	CFPA htr DISABLED
285-14:49:26.3	Blackbody htr DISABLED
285-14:49:48.9	Baffle htr DISABLED
285-14:51:09.1	Procedure POSTDELI started.
285-14:52:06.6	RTCS 19 = INVALID
285-14:52:37.2	Procedure POSTDELI completed.
285-14:52:44.4	Prime/Redundant Catbed htrs OFF
**************	**
285-15:09:11.0	SGS 7937
285-15:14:14.5	Post-burn Ephemeris uplink complete
285-15:18:55.7	Procedure POSTDELI started.
285-15:19:06.9	Skew wheel = ENABLED
285-15:20:13.3	ACS limits = FINE
**************	**
285-15:23:46.0	LGS 7937
285-15/25/17.5	PRADS filter converged
285-15:28:18.1	Reset TEMPBIAS scale values
**************	**
285-15:23:46.0	TDS 7937
285-15:43:20.2	Procedure DATAB started.
285-15:43:29.6	entered DATAB 1
285-15:46:20.0	Reset Slew Quaternion
285-15:46:44.6	Procedure DATAB started.

Appendix - A - Detailed Timeline of Events

285-15:46:51.8	entered DATAB 2 state
285-15:48:00.0	Procedure RTCSCONFIG started.
285-15:48:11.4	RTCS_19 = VALID
285-15:48:34.4	Procedure RTCSCONFIG started.
285-15:48:45.4	RTCS 22 = INVALID
**************	***
286-01:23:00.0	WSC 7943
286-01:24:02.5	Blackbody htr ENABLED
286-01:24:37.9	Blackbody T3 selected
**************	***
286-09:41:21.5	WSC 7948
286-09:42:19.7	Baffle htr ENABLED
**************	***
286-17:45:58.3	LGS 7953
286-17:47:29.1	CFPA htr ENABLED
**************	***